



## MEAD retrospective analysis report

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*Publication date:*  
2003

*Document Version*  
Publisher's PDF, also known as Version of record

[Link back to DTU Orbit](#)

*Citation (APA):*  
Hasager, C. B., Carstensen, J., Frohn, L. M., Gustafson, B., Brandt, J., Conley, D., Geernaert, G., Henriksen, P., Skjøth, C. A., & Johnsson, M. (2003). *MEAD retrospective analysis report*. Denmark. Forskningscenter Risoe. Risoe-R No. 1385(EN)

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# **MEAD Retrospective Analysis Report**

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## **Abstract.**

The retrospective analysis investigates links between atmospheric nitrogen deposition and algal bloom development. The analysis covers the Kattegat Sea in the summer periods from April to September during the years 1989-1999. The retrospective analysis is based on atmospheric deposition model results, hydrodynamic deep-water flux results, phytoplankton abundance observations from Danish and Swedish marine monitoring stations and optical satellite data.

The atmospheric results are from the ACDEP atmospheric-chemistry model and the hydrodynamic results are from a basin-scale hydrodynamic model used to estimate the flux of nutrients to the mixed layer by wind forced entrainment. The results are presented as time series of total atmospheric nitrogen deposition, atmospheric wet deposition together with nitrogen fluxes from the bottom waters to the surface layer. Approximately 70 % of the atmospheric deposition consists of wet deposition of highly episodic nature. The atmospheric deposition of nitrogen is of the same order of magnitude as the flux from the bottom waters. Yet the cumulative atmospheric deposition is always larger than the marine deep-water flux.

The atmospheric deposition and deep-water nutrient fluxes have been analysed statistically to observations of chlorophyll and biomass in the Kattegat Sea. Based on this analysis it is found that atmospheric deposition is on average the largest source of external nitrogen to the top 10 m water column in the summer period. However, the mixing of nutrient-rich water from below the pycnocline into the euphotic zone is a process of highly episodic character and provides sufficient nitrogen to the euphotic zone to sustain larger algae blooms. The two nitrogen loading processes are correlated – mainly because both are to some extent related to the wind velocity – and the nitrogen input from both processes enables the build-up of algae blooms. Furthermore, the nitrogen supplied on a single day cannot sustain a bloom with an increase above 0.5 µg/l chlorophyll a, but several consecutive days of high nitrogen inputs create the potential for blooms.

The distributions of chlorophyll a in terms of both mean and extreme values have large spatial variations. Areas with high chlorophyll a concentrations are close to major freshwater sources with high nutrient loading or in the frontal zone in the northern part, where Kattegat water mixes with high saline water from Skagerrak. The spatial distribution of frequency of blooms results in a different picture. Areas that are hydrographically active with high turbulent mixing have the highest frequency of blooms. These areas are the frontal zone in Northern Kattegat, the outflow areas in Southern Kattegat where Baltic Sea water is diverted through the Great Belt or the Sound.

The physical and chemical conditions before and during a bloom revealed that blooms occurred under higher salinity and wind conditions on 2-6 days prior to the observed bloom. Blooms were dominated by diatoms and dinoflagellates species – mainly *Rhizosolenia* spp. and *Ceratium* spp. *Ceratium* is a species, which typically is observed around the pycnocline, but it can be mixed up into the euphotic zone and remain in the surface layer provided that nutrient conditions are favorable. Thus, the phytoplankton composition indicate together with increased DIN and DSi that blooms are most likely due to wind-forced mixing of nutrient-rich bottom water into the surface layer. Four algal blooms events were identified in the years 1990-1992.

ISBN 87-550-3164-1 (Internet)  
ISSN 0106-2840

Print: Pitney Bowes Management Services Denmark A/S, 2003

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# 1 Introduction

## 1.1 Project summary

Marine Effects of Atmospheric Deposition (MEAD) is a research, technology and development (RTD) project funded by the European Union, under its 5<sup>th</sup> Framework Programme contract EVK3-CT-1999-00014.

The MEAD project is an international project co-ordinated by Professor Tim Jickells and Dr. Lucinda Spokes, UEA. The partners include English, Danish and Swedish researchers from a number of institutes. For an overview of the project and its participants please refer to <http://www.uea.ac.uk/env/mead>.

The MEAD project focus on atmospheric, marine and environmental processes is the Kattegat Sea between Denmark and Sweden in order to investigate the effects of atmospheric nitrogen deposition to the sea, with a special emphasis on algal bloom.

Within the MEAD project there is a number of work packages, deliverables and milestones. One of the work packages is a retrospective analysis. Part of this work is documented in the present report and in scientific written, oral and poster presentations.

## 1.2 Objective

The overall objective of the MEAD project is to describe the effects of atmospheric nitrogen deposition on coastal water biogeochemistry.

The MEAD project work includes 6 specific objectives (please refer to <http://www.uea.ac.uk/env/mead>). One of these specific objectives is the following:

### 1.2.1 Specific objective

- ◆ Retrospective analysis of existing atmospheric deposition, phytoplankton abundance and satellite imagery data to investigate any links between atmospheric nitrogen deposition and bloom development.

The report and the data matrix containing the data used for the analysis is the Deliverable 3 in the MEAD project.

### 1.2.2 Deliverables

- ◆ Statistical reliability of the atmospheric deposition measurements as indicators of upcoming algal blooms, as a function of time of year and parameters representing environmental preconditioning.
- ◆ Data matrix of atmospheric and oceanographic nutrient fluxes and algal blooms, containing meteorological, air chemistry, and water chemistry measurements, as well as satellite imagery.

The data matrix is available at <http://www.dmu.dk/AtmosphericEnvironment/MEAD> and is documented in the report in section 3.

### **1.3 Description of work**

The retrospective analysis is a statistical investigation of the occurrences of algal blooms in the Kattegat Sea in previous years based on marine-, atmospheric- and satellite-data. To increase our physical and biological understanding, atmospheric- and hydrodynamic models are used to assess processes that may have occurred within the last decade (1989-1999) with special emphasis on extreme events in the summer periods (May to August).

Marine biogeophysical data archives in Denmark and in Sweden are used. Atmospheric data archives and model results as well as model results of the hydrodynamic processes of vertical nutrient transport on the halocline are investigated. Satellite data is investigated to provide spatial patterns and weather conditions.

There are existing programmes that monitor phytoplankton abundance in coastal waters of the Kattegat run by local agencies in Denmark and Sweden as part of routine monitoring work. This data is synthesised into a common matrix and used to identify and characterize phytoplankton blooms in this area. The areas and temporal extent of these blooms is evaluated using archived satellite imagery (NOAA AVHRR).

Data from a monitoring station at the island Anholt is searched to identify high deposition events. The causal relationship between blooms and deposition events is investigated using multivariate statistical techniques. The relationship of blooms to other biogeochemical and physical variables is evaluated over short (daily) to long (inter-annual) time scales.

### **1.4 Expected results and exploitation plans**

The expected result is a more detailed understanding of possible cause-effect relations in the atmospheric-marine coastal environment from a statistical view point.

The exploitation plan is to set-up realistic scenario model runs based on the statistical knowledge on cause-effect relations. The MEAD project scenario modeling on combining atmospheric and marine models and data (work package 6) is built on case studies. The more relevant cases will have to be chosen and to this end the retrospective analysis results will be used as a guide for selection.

# **2 Retrospective analysis on algal blooms in the Kattegat Sea**

## **2.1 Description of the retrospective analysis methodology**

Existing Danish and Swedish monitoring data bases applicable to the Kattegat is assembled into a common matrix for the months, May through August 1989-1999. The data matrix includes the measurements made of atmospheric deposition, water chemistry and phytoplankton species composition (including harmful algae) for the top 10 meters of the water column and meteorology as well as modeling of atmospheric deposition on daily, weekly and monthly time scales. In addition, satellite imagery is examined for the periods when in-situ observations indicated moderate to severe algal blooms in order to determine the extent and duration of blooms.

Using the matrix of databases, multivariate statistical analyses are carried out to determine cause-effect relationships between atmospheric deposition and marine biological states. The aim was to infer seasonal and inter-annual controls on coastal eutrophication risk assessment.

The following issues (tasks) are addressed:

- ◆ Determine the frequency of occurrence of extreme deposition events and phytoplankton blooms, including harmful algal blooms, using the Kattegat as a region of study.
- ◆ Establish the statistical relationship between deposition events and subsequent occurrence of phytoplankton blooms, including harmful algal blooms, based on a long time series of atmospheric and oceanic monitoring data bases in Denmark and Sweden.
- ◆ Determine the atmospheric and oceanographic conditions under which algal blooms develop, where meteorological controls, emission patterns, season, nutrient transport, and nutrient load history are considered. Inter-annual variability is also examined.



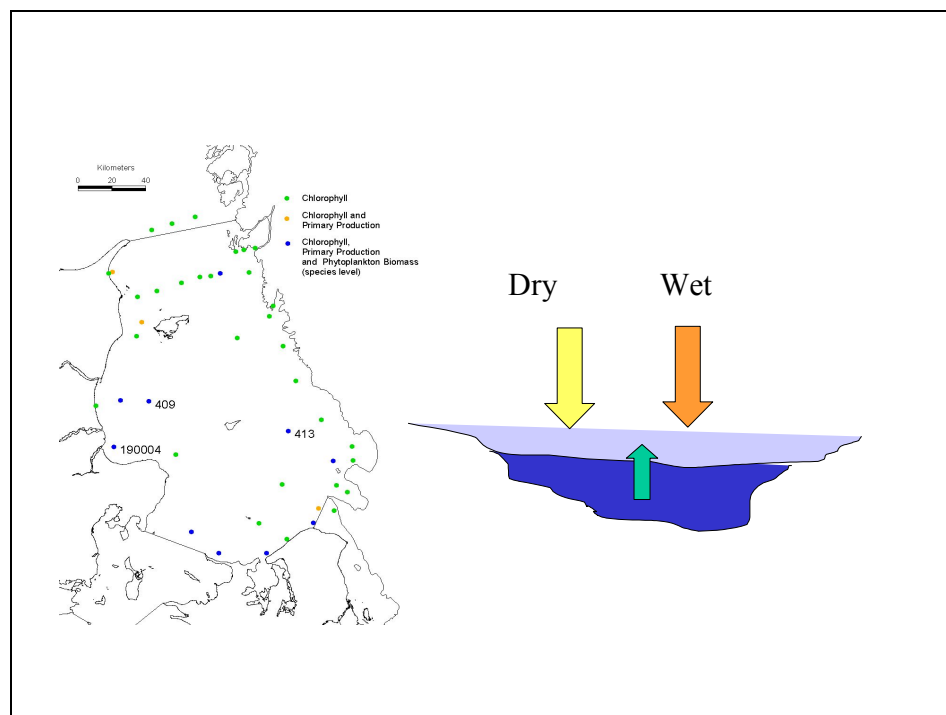


Figure 2.1. Concept graph (map of vertical cut of the sea- west east). The study involves wet and dry atmospheric deposition and deep water flux and the associated algae bloom responses to these inputs to the surface water layer.

## 2.2 Description of data

### 2.2.1 Marine observations

A data matrix comprised of data from the Danish (source: NERI) and Swedish (source: SMHI) national monitoring programs has been assembled (see section 3.5). For the retrospective analysis data from summer months (May-August) from 1989-1999 were used in order to eliminate spring and autumn blooms from the data matrix. The spatial coverage of data was good with the majority of stations located in the coastal areas. Stations in marine areas bordering Kattegat were also selected.

The study has mainly been concerned with measurements related to phytoplankton, i.e. chlorophyll a concentrations, primary production and biomass, but other measurements were included as well as explanatory variables (salinity, temperature, nutrients). Chlorophyll a was available from 50 stations, chlorophyll a and primary production were available from 14 stations, and chlorophyll a, primary production and biomass were available from 11 stations. Primary production and phytoplankton biomass were only available from Danish monitoring stations (Fig. 2.1).

Kattegat is normally considered well-mixed down to 10-15 m below the surface, where a salinity gradient separates the less saline water originating from the Baltic Sea from the more saline water originating from the Skagerrak. In the summer period nutrients are depleted from the upper well-mixed zone. Therefore, samples from the top 10 meters of the water column are considered only for assessing the effect of atmospheric deposition. Salinity, temperature, DIN,

DIP and chlorophyll a measurements were averaged over the top 10 m water column. Furthermore, the salinity and temperature stratification was calculated as the difference between surface and bottom samples of salinity and temperature.

*Table 2.2-1: Descriptive statistics of data matrix for marine data.*

Year	Number of observations			Summer averages		
	Chla	P.Prod.	Biomass	Chla mg/m <sup>3</sup>	P.Prod. mg C/m <sup>2</sup> /d	Biomass mg C/m <sup>3</sup>
1989	78	30	22	1.94	530	126.5
1990	100	43	35	2.40	647	92.2
1991	106	46	40	2.03	550	132.4
1992	98	51	41	2.11	617	81.4 <sup>1</sup>
1993	168	60	39	1.80	405	64.6
1994	176	64	51	2.11	518	57.1
1995	202	64	55	1.95	475	47.8
1996	139	53	49	1.56	410	45.9
1997	186	52	30	1.41	440	66.3
1998	153	7	32	2.11	726	92.7
1999	187	12	42	1.91	632	107.1

<sup>1</sup>One observation from station 3310 was very extreme and not included in this descriptive analysis

The amount of data and averages of the three important phytoplankton variables are summarized in Table 2.2-1. The number of primary production measurements was low in 1998 and 1999 due to a change in the strategy of the national monitoring program in Denmark.

### **2.2.2 Atmospheric data**

As part of the project component “retrospective analysis”, the objective of NERI’s Department of Atmospheric Environments work is to examine the historical record of atmospheric deposition, with special reference to the frequency of occurrence and duration of events that contain significant atmospheric deposition of nutrients to the Kattegat. This combines measurements from the station Anholt, and a reconstruction of model derived patterns of deposition. To compile statistically relevant results, the model calculations must be based on fine spatial resolution and very short temporal resolutions.

### **2.2.3 Anholt data**

The station of Anholt is maintained by NERI and has been in use since 1988. Wet depositions and precipitation measurements with 14 days resolution are available from 1989 until 1999. The wet deposition samples are analysed for ammonium (NH<sub>4</sub><sup>+</sup>) and sulphate (SO<sub>4</sub><sup>2-</sup>). Also nitrate and nitric acid is measured as a sum.

#### 2.2.4 ACDEP model results

Model results of atmospheric deposition are available from the ACDEP (Atmospheric Chemistry and DEPosition) model for the period 1989-1999. Depositions have been obtained for the compounds  $\text{HNO}_3$ ,  $\text{NH}_3$ ,  $\text{NH}_4^+$ ,  $\text{NO}_2$  and  $\text{NO}_3^-$  on daily, monthly and yearly basis. Time series on a daily scale for wet and dry N deposition and total N deposition to the Kattegat area as well as time series on a daily scale for wind speed and direction in the Kattegat area are available for the period 1989-1999.

## 3 Data matrix – a deliverable of the Retrospective Analysis

### 3.1 Description of data matrix

The data matrix is accessible at

<http://www.dmu.dk/AtmosphericEnvironment/MEAD>

Data and model results are calculated for the years 1989-1999 and for summers only, i.e. May 1<sup>st</sup> to August 31<sup>st</sup>.

### 3.2 Atmospheric data from Anholt

The Anholt station is one of 8 operational stations maintained by NERI. It is located in the middle of Kattegat (see Figure 3.1) at 657 km E, 6287 km N. At the Anholt station NERI measures air-concentrations of ammonia ( $\text{NH}_3$ ), particle-bound ammonium ( $\text{NH}_4^+$ ), nitric acid ( $\text{HNO}_3$ ) and particle-bound nitrate ( $\text{NO}_3^-$ ). All compounds are measured on a daily basis using the filter-pack method. Furthermore nitrogen dioxide ( $\text{NO}_2$ ) is measured on a daily basis using glass filters, see (Ellermann *et.al.* 1996) for a more detailed description. The precipitation and wet deposition of ammonium and sulphate ( $\text{SO}_4^{2-}$ ) is measured with 14 days time span.

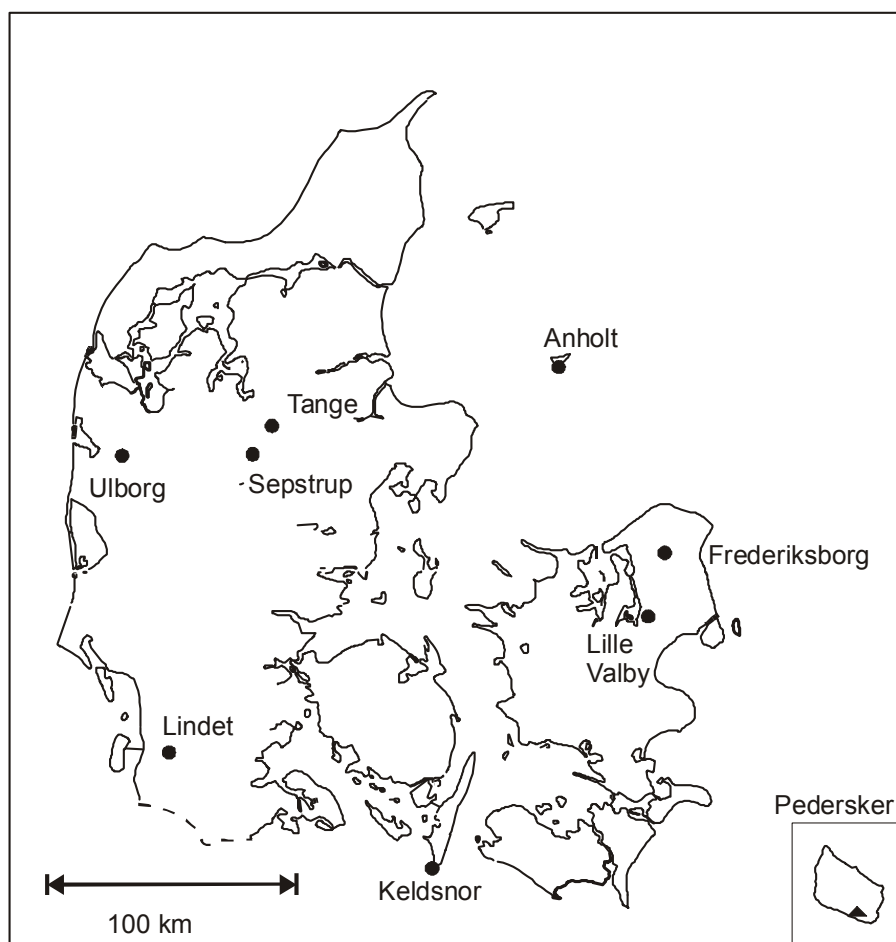
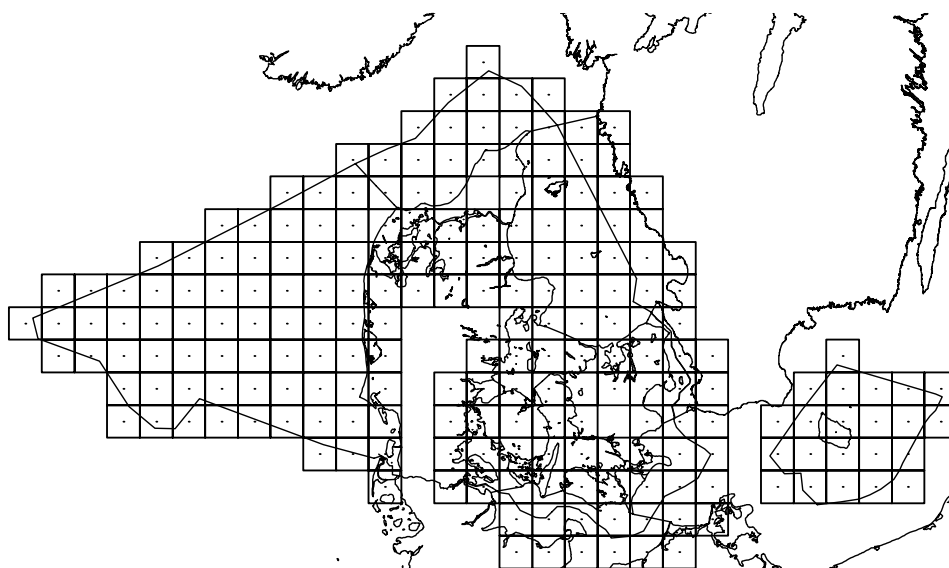


Figure 3.1. Measuring stations operated by NERI under NOVA (Ellermann et al. 2000). (●) Stations measuring wet deposition and air concentrations. (▲) Station measuring wet deposition only.

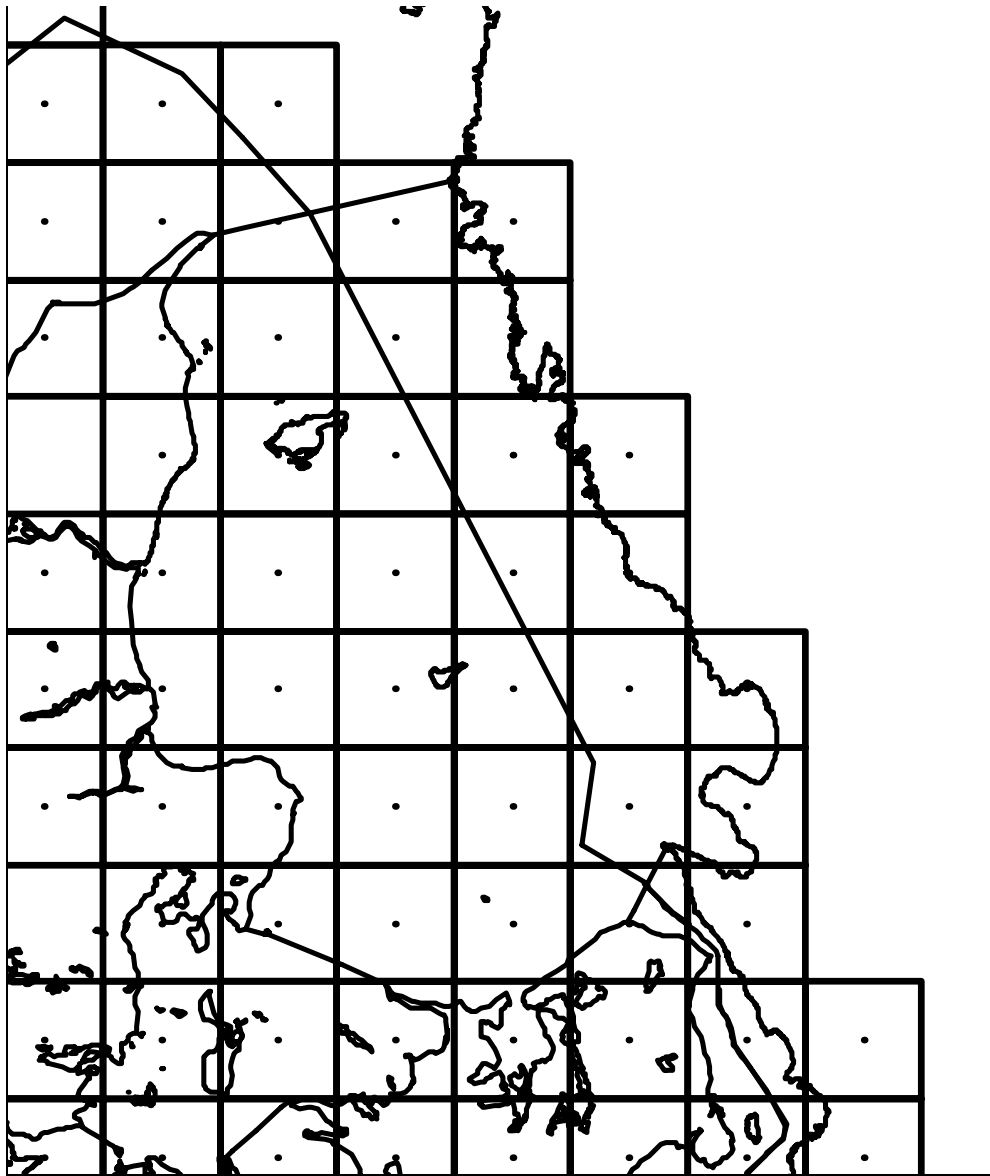
### 3.3 Atmospheric ACDEP model results

The ACDEP receptornet for all of Denmark covers the area graphed in Fig. 3.2.



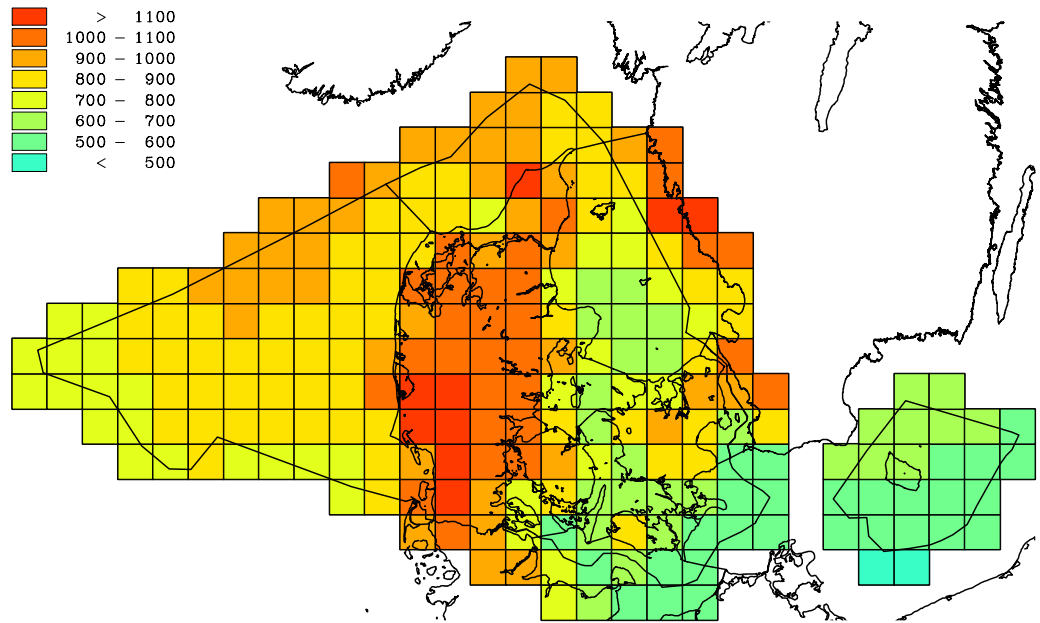
*Figure 3.2. The grid used for the ACDEP model calculations with a resolution of 30 km x 30 km for the Danish marine waters. The dots designate the receptor points (233 in total) for which the calculations are carried out. Furthermore the borders between the different marine waters are drawn. Information concerning, which water the different grid cells belong to has been obtained from data provided by The Geological Survey of Denmark and Greenland.*

The ACDEP model results, for the Kattegat area, have a resolution of 30 km x 30 km. The Kattegat area extends from the Northern Beltsea and Øresund in the south to the Skagerrak in the north and covers 23,583 km<sup>2</sup>. The model grid for the Kattegat region can be seen in Figure 3.3. The model results consist of daily total N depositions and accumulated daily precipitation as well as average wind speed and wind direction. Depositions are distributed on wet and dry depositions, as well as on depositions of ammonium (NH<sub>4</sub><sup>+</sup>) and nitrate (NO<sub>3</sub><sup>-</sup>). Deposition units are kg N per km<sup>2</sup>, which corresponds to mg N per m<sup>2</sup>. Precipitation is given in mm, wind speed in m/s and wind direction in degrees.

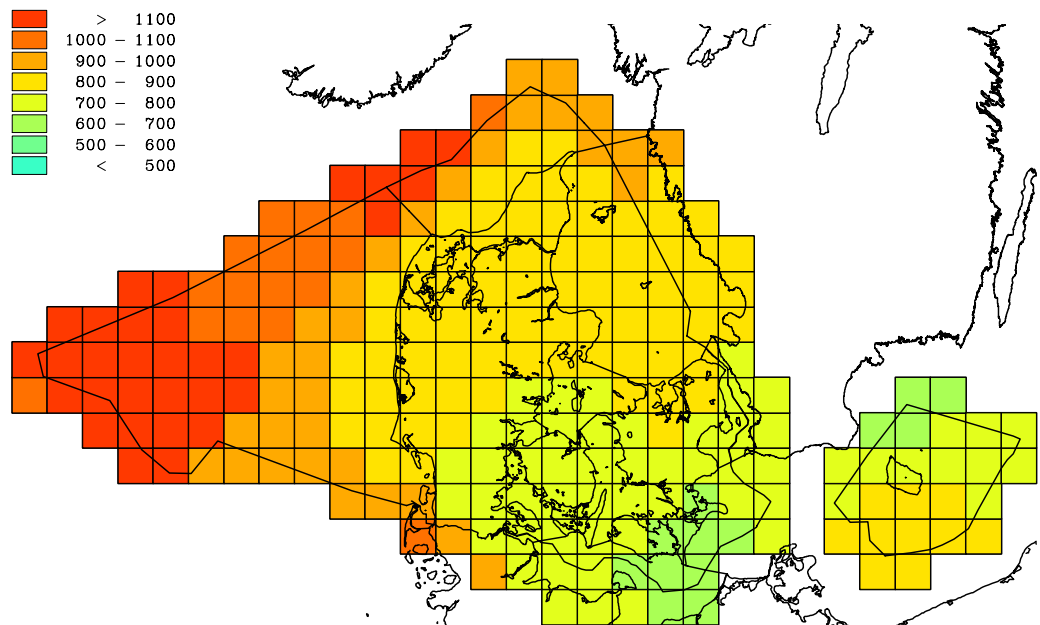


*Figure 3.3. The model grid for the Kattegat region used in the MEAD investigations. Anholt is the small island located in the middle of Kattegat.*

Until the year 1998 the ACDEP model has been run with meteorological data provided by the European Monitoring and Evaluation Programme (EMEP) on a 150 km x 150 km grid with a 6 hour resolution. In 1999 these data have been substituted with results from the operational weather forecast model Eta (Nickovic, 1998) that is run operationally at NERI and delivers results on an hourly basis. Preliminary investigations of the results from the Eta model indicate that these data are of good quality. Pressure and temperature fields from the Eta model for the Danish land areas seem to correlate better with measurements than the EMEP data. Furthermore the Eta data also seem to have a smaller bias. A short investigation of precipitation fields in general shows a clear land/sea effect in the precipitation rates which can be seen in the Eta fields from 1999 (Figure 3.4) but not in the EMEP fields from 1998 (Figure 3.5).



*Figure 3.4. Amount and distribution of total precipitation for the year 1999 as calculated with the Eta model.*



*Figure 3.5. Amount and distribution of total precipitation for the year 1998. Data delivered by EMEP.*

It is concluded that, trajectories calculated for the ACDEP model using Eta data (1999) will incorporate the hourly physical parameters directly from the meteorological model, while trajectories calculated on the basis of the EMEP meteorological fields (1989-1998) will be based on the interpolated hourly physical parameters. Unfortunately Eta model results are not available for the period 1989-1998.

### 3.4 Hydrodynamic model results

The daily time-series statistics of vertical nutrient transport (fluxes) through the halocline using a hydrodynamic model combined with observed nutrients in the Kattegat area is produced.

An existing hydrodynamic model applied to the Kattegat (Gustafsson, 2000) has been adapted to calculate nutrient fluxes. Observed monthly relationships between nutrient concentrations and salinity are combined with the model results to obtain estimates of the fluxes. Recently horizontal advective fluxes between 1974 and 1999 have been quantified (Rasmussen and Gustafsson, 2003). By a slight modification daily time-series of vertical nutrient fluxes is calculated. Although the method is somewhat insecure, the results provide a good basis for comparison between extreme atmospheric depositions and events of vertical entrainment of nutrients into the surface mixed layer.

This data set comprises of daily vertical fluxes of inorganic nitrogen and phosphorus into the surface mixed layer. The computational method is described in Chapter 7 of this report. The time-series cover the period 1975-99 and resolves spatial variation with three sub-basins, northern, central and southern Kattegat (the surface areas of these basins are given in Table 2.2). The fluxes are given in mgN/m<sup>2</sup>/day.

*Table 2.2. Surface areas of the sub-basins*

Sub-basin	Area (km <sup>2</sup> )
Northern Kattegat	5069
Central Kattegat	8118
Southern Kattegat	9100

### 3.5 Marine data

The marine data has been assembled in to a data matrix, which is available as an Excel spreadsheet ('marine data matrix.xls'). The sheet consists of 28 columns, which are described below with units in parentheses:

- A: Identification of station number
- B: Date of sampling
- C: Total biomass of cyanobacteria (mg C/m<sup>3</sup>)
- D: Total biomass of dinoflagellates (mg C/m<sup>3</sup>)
- E: Total biomass of diatoms (mg C/m<sup>3</sup>)
- F: Total biomass of Mesodinium Rubrum (mg C/m<sup>3</sup>)
- G: Total biomass of other species not included in C-F (mg C/m<sup>3</sup>)
- H: Identification of dominating cyanobacteria species by biomass
- I: Identification of dominating dinoflagellate species by biomass
- J: Identification of dominating diatom species by biomass
- K: Identification Mesodinium Rubrum
- L: Identification of dominating other species by biomass
- M: Biomass of dominating cyanobacteria species (mg C/m<sup>3</sup>)
- N: Biomass of dominating dinoflagellate species (mg C/m<sup>3</sup>)
- O: Biomass of dominating diatom species (mg C/m<sup>3</sup>)
- P: Biomass of Mesodinium Rubrum (same as F) (mg C/m<sup>3</sup>)



Q: Biomass of dominating other species (mg C/m<sup>3</sup>)  
 R: Total phytoplankton biomass (sum of C-G) (mg C/m<sup>3</sup>)  
 S: Total nitrogen (TN) in top 10 m (μmol/l)  
 T: Total phosphorus (TP) in top 10 m (μmol/l)  
 U: Salinity in top 10 m (psu)  
 V: Dissolved inorganic nitrogen (DIN) in top 10 m (μmol/l)  
 W: Dissolved inorganic phosphorus (DIP) in top 10 m (μmol/l)  
 X: Chlorophyll a concentration in top 10 m (μg/l)  
 Y: Dissolved silicium (DSi) in top 10 m (μmol/l)  
 Z: Temperature in top 10 m (C)  
 AA: Salinity stratification (top-bottom) (psu)  
 AB: Temperature stratification (top-bottom) (psu)  
 AC: Area primary production (mg C/m<sup>2</sup>/d)

### 3.6 Atmospheric data – airports

Meteorological data provided by The Danish Meteorological Institute were used in the statistical analysis of marine data. The data consist of time series from 1989 to 1998 of wind speed and direction for the airports Aalborg and Kastrup. The data is not available in the data matrix.

### 3.7 Satellite data

NOAA AVHRR quicklooks from Dundee, UK.

Raw NOAA AVHRR data from northern Europe are archived at <http://www.sat.dundee.ac.uk> and quicklooks are available from nov. 1978 to present, though with some gaps. Typically two daily scenes with a 1 km spatial resolution are available.

NOAA AVHRR Sea Surface Temperature (SST) from NASA pathfinder, USA.

Processed data on the global sea surface temperature (SST) are archived in the NASA Pathfinder archives. At <http://podaac.jpl.nasa.gov> globally gridded products are available e.g. a 9 km resolution at a daily time scale spanning jan. 1987 to nov. 1999.

## 4 Bloom frequency and magnitude in Kattegat

Phytoplankton in marine waters is generally considered to be nitrogen limited during the summer period (Granéli 1987). Nitrogen enhances the primary production and is delivered to the photic zone by atmospheric deposition, land-based runoff, nutrient fluxes across the pycnocline, and recycling of nitrogen in the photic zone.

Studies have shown that the atmospheric contribution of nitrogen is approximately 30-40% of the total external loading to Kattegat (Asman *et al.* 1994) and that during the summer period atmospheric nitrogen input may exceed the land-

based runoff of nitrogen. Moreover, most of the land-based runoff of nitrogen will only affect the coastal zone as this contribution is used for production before being advected to the open sea. The magnitude of nitrogen supply from below the pycnocline and recycling of nitrogen has not yet been quantified for the Kattegat. However, recycling of nitrogen will not be able to sustain larger algae blooms as this is an internal source. Thus, the nitrogen required to sustain larger algae blooms in the open sea can be of either atmospheric origin or from below the pycnocline. While the supply of nitrogen from the atmosphere has a typical episodic character, the build-up and breakdown of stratification is a more conservative process.

The objective of this particular study for marine observations is to:

- Identify bloom events that could potentially have been fuelled by an atmospheric deposition event.
- To determine the frequency and spatial distribution of algae blooms in Kattegat

## 4.1 Methods

The spatial distribution of the mean surface chlorophyll a concentration was calculated using a Kriging interpolation based on a linear variogram model (Cressie, 1993). Gamma distributions were fitted to the chlorophyll a measurements from each station individually. The Gamma distribution constituted a better model for data than alternative distribution models (Normal, Lognormal and Weibull). Using the estimated Gamma distributions, the percentiles of the distribution corresponding to a wide range of return periods were determined.

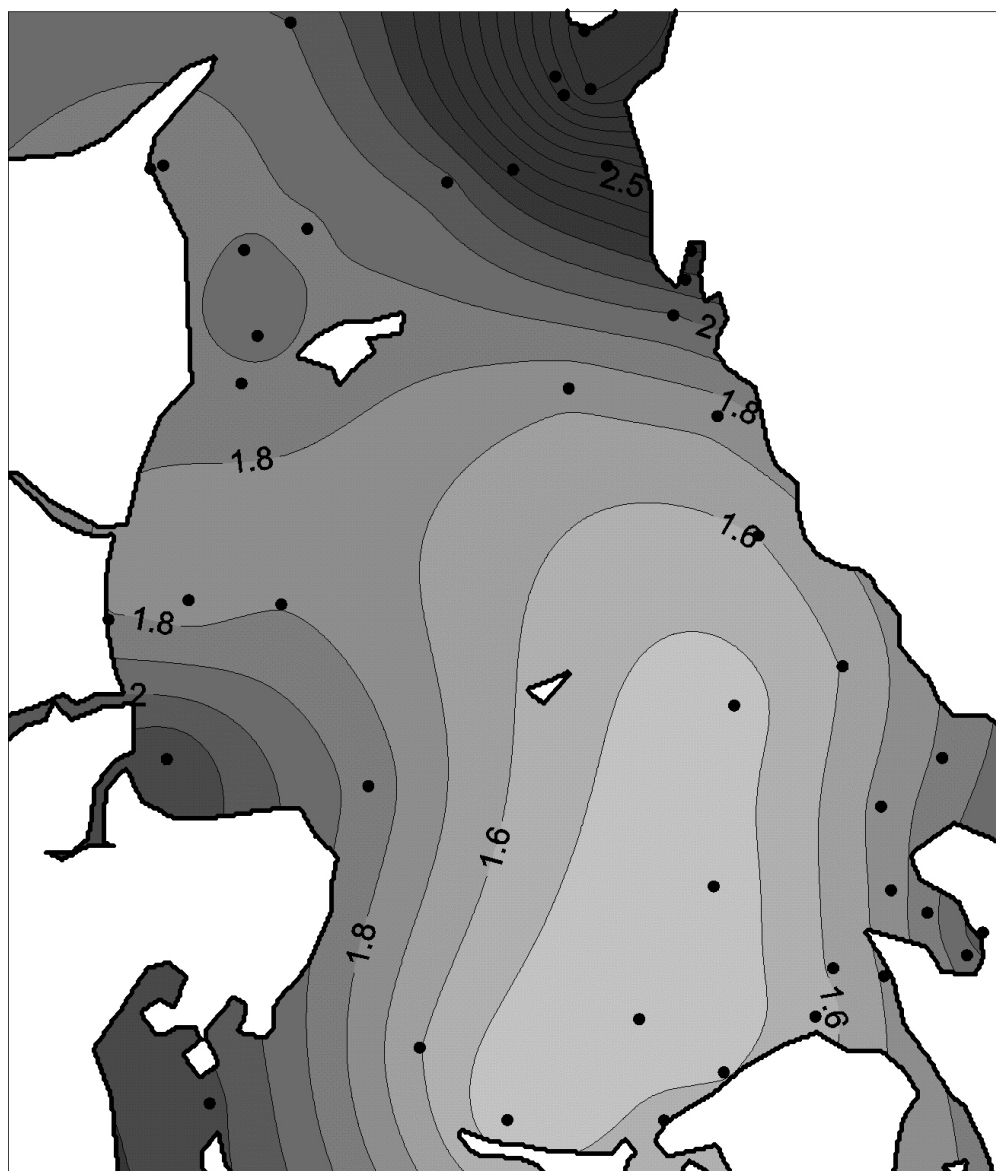
An operational definition of a bloom event based on the distribution of chlorophyll a has been formulated and chlorophyll a data have been segregated into bloom and non-bloom situations. The spatial distribution for the relative frequency of bloom events was analysed using a Kriging interpolation. Finally, changing conditions in salinity, stratification and wind speed between bloom and non-bloom events was analysed using a two-way Analysis Of Variance (ANOVA) with bloom versus non-bloom, station and the interaction between bloom and station as factors. The dominating species in the identified bloom situations were determined from phytoplankton biomass concentrations.

## 4.2 Results

The spatial distribution of the mean summer chlorophyll a concentration in the surface layer is shown in Figure 4.1. There were large inhomogeneities in the spatial pattern revealing high algae concentrations in

1. the Göta River estuary in the north-eastern corner of Kattegat
2. Hevring Bugt in the south-western corner of Kattegat
3. North-west of the island of Læsø

Hevring Bugt and Göta River estuary are dominated by freshwater runoff from Gudenåen and Göta River, respectively. North of Læsø there is a front, where saline surface water from the Skagerrak meets the less saline surface water of Kattegat. Lowest concentrations were observed in the off-coastal area in the southeastern part of Kattegat.



*Figure 4.1. The spatial distribution of average surface chlorophyll a (May-August in 1989-99) in Kattegat. The contour plot is produced using the Kriging interpolation method. Dots show the location of Danish and Swedish stations used for the analysis.*

The empirical distribution of chlorophyll a also revealed significant differences between coastal and open sea stations. The Gamma distributions fitted to data from two stations representing the shallow coastal zone and the deeper open sea are shown in Figure 4.2 with calculated chlorophyll a concentrations versus return periods between 1 and 12 years. The results show that blooms of a given magnitude will occur much more frequent at the coastal station.

This pattern is illustrated for all stations in Kattegat in Figure 4.3, where the spatial distribution of chlorophyll a in a bloom that will occur every 10 years is shown. The figure shows that even though the south-western corner of Kattegat showed high chlorophyll concentrations, we should expect blooms of highest magnitude in the northern part of Kattegat, which is a frontal zone. The southern central part of Kattegat appears to be least exposed to large summer blooms.

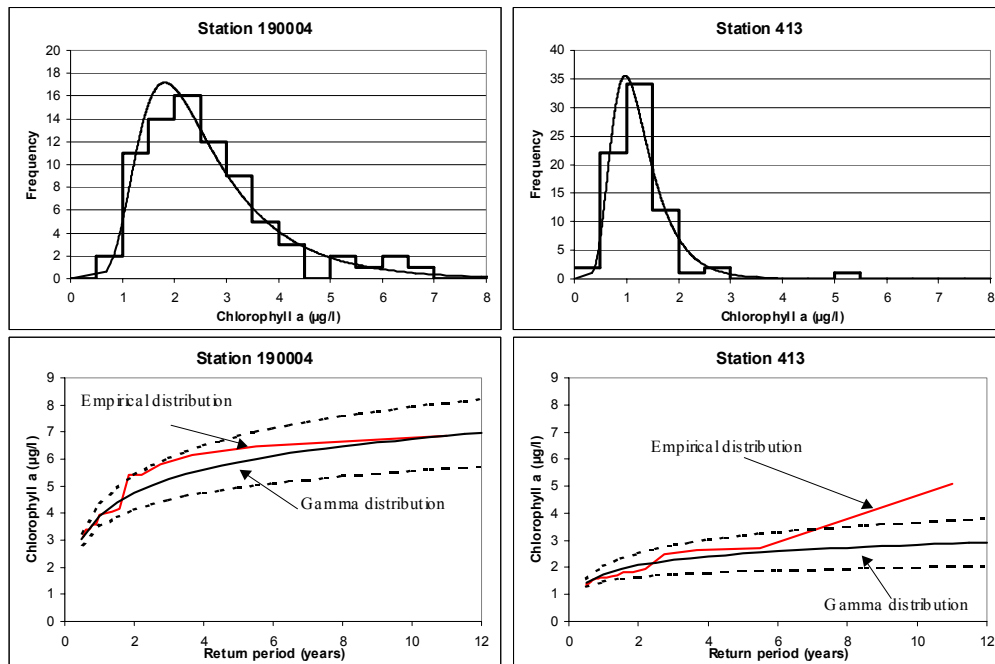


Figure 4.2. The upper graphs show the empirical and estimated Gamma distribution for summer surface chlorophyll a at a coastal station (Station 190004) and an open sea station (Station 413). Lower graphs show chlorophyll a concentrations as a function of return period calculated from the empirical and Gamma distribution.

Figure 4.4. shows the results of applying the operational bloom definition to two stations in Kattegat. It is observed that the definition classifies all the high chlorophyll observations into the group of bloom events. Although the two groups of blooms and non-blooms are not totally distinct, the classification appears reasonable. Out of a total of 1786 chlorophyll a observations 233 were classified as bloom events. Figure 4.5 shows the spatial pattern for the relative frequency of bloom events for Kattegat. Three areas in Kattegat were identified as zones with a higher probability of generating blooms, the southern part where the Great Belt and the Sound flow into Kattegat and the frontal zone where Skagerrak mixes with Kattegat. These three areas are characterised by strong periodic turbulent mixing.

Observations of bloom versus non-bloom situations were related to variables using a two-way ANOVA to describe the conditions for a bloom. The results are shown in Table 4.1. For the physical and chemical variables in the water column a significant station effect was found for all variables except temperature, which did not appear to have a significant spatial pattern. Only salinity showed a general difference between bloom and non-bloom situations with a mean increase in salinity of 0.73 psu during blooms. Temperature decreased during blooms although not significantly. There was no effect on the stratification for bloom versus non-bloom situations.



*Figure 4.3. The spatial distribution of expected chlorophyll a level with a 10 year return period based on weekly independent samples.*

For nutrients there was no consistent difference between bloom and non-bloom situation, but the cross effect of station and bloom was significant for DIN and DSi. When the analysis of DIN and DSi was carried out stationwise, 3 and 7 stations gave a significant difference between bloom and non-bloom situations for DIN and DSi, respectively. One station (Skalkorgarne) located in the Göta River estuary showed declines in DIN and DSi during blooms, while all other significant stations showed inclines in DIN and DSi. The majority of stations showing significant inclines in DSi were open sea stations. Increases in DSi cannot be due to atmospheric deposition and can only be caused by mixing of deeper water into the surface layer.

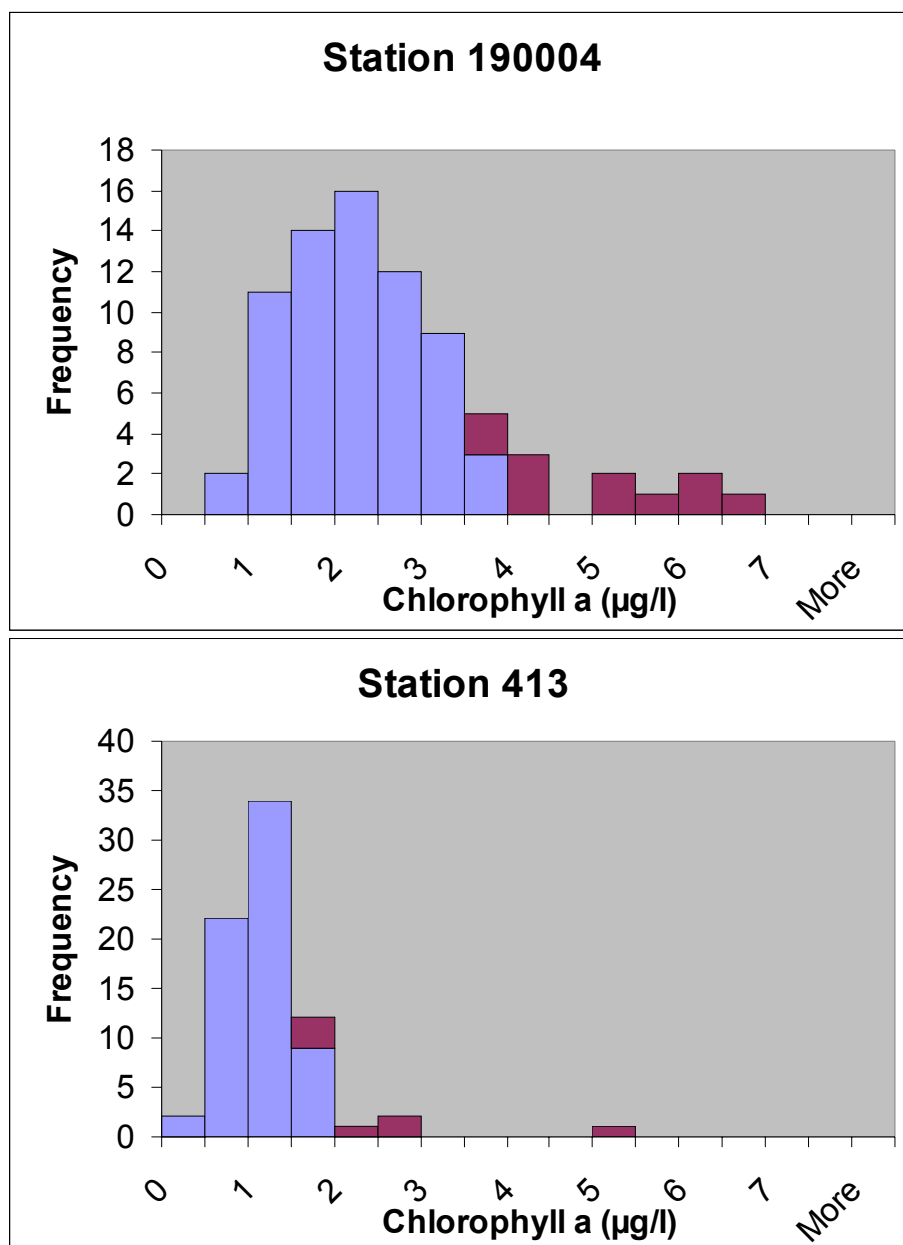
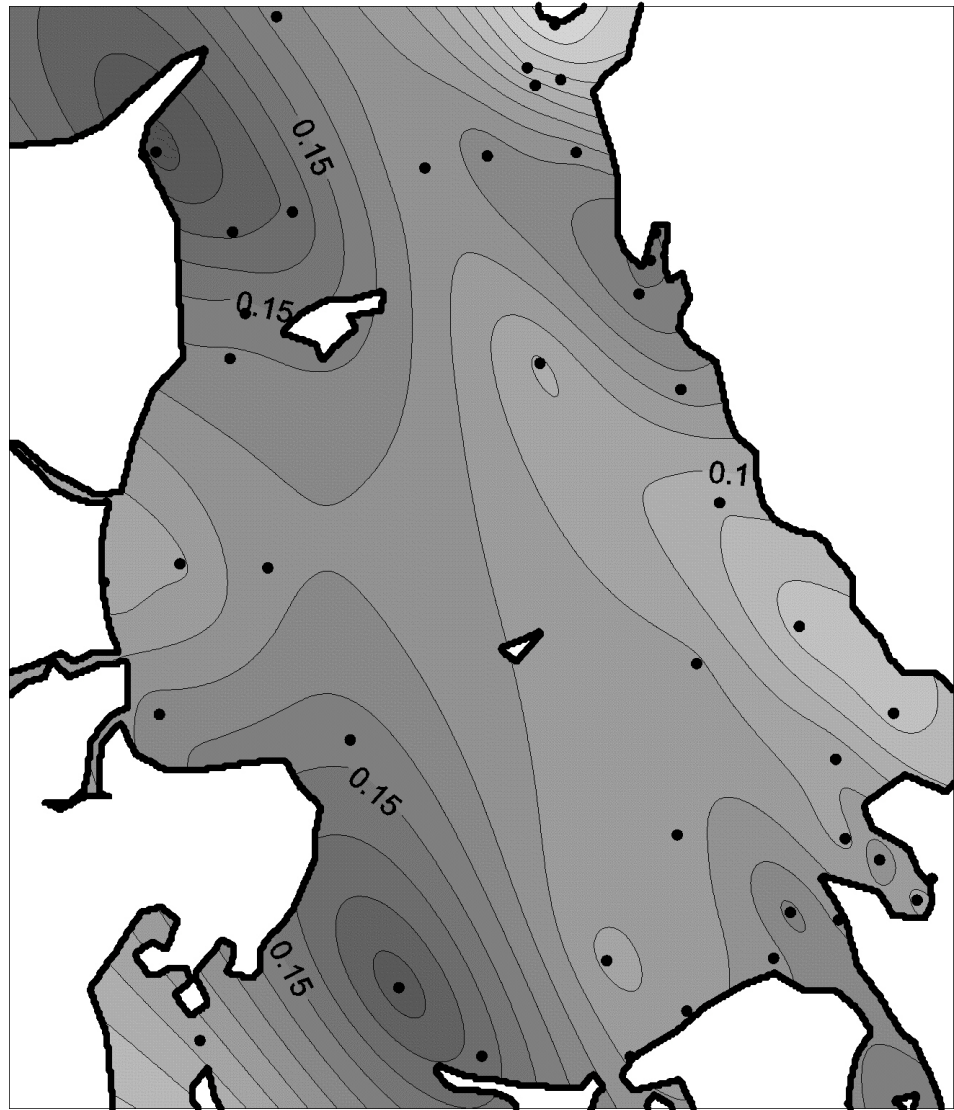


Figure 4.4. Distribution of chlorophyll a separated into bloom (dark grey) and non-bloom (bright grey) events.

The spatial differences between stations could not be investigated for mean daily winds (lagged 0-10 days), because the wind velocity was calculated as a single variable for all Kattegat. The data consists of the average from Ålborg and Kastrup Airports (see section 3.6). Significant increases in wind velocities for sampling day and 2-6 days prior to the sampling day were found for blooms with increases in wind velocity ranging from 0.24-0.49 m/s. A significant negative difference in wind velocity between bloom and non-bloom situations was also observed for the wind lagged 8 days, but this result is considered to be an artifact.





*Figure 4.5. The spatial distribution of the relative frequency of algae blooms in Kattegat. The contour plot is produced using the Kriging interpolation method. Dots show the location of Danish and Swedish stations used for the analysis.*

The results indicate that blooms were most likely caused by entrainment of nutrient-rich bottom water into the surface layer. However, we cannot exclude the effect of atmospheric deposition, which could potentially contribute to blooms as well. We would not anticipate that blooms fuelled by atmospheric deposition would yield significant differences in any of the physical or chemical variables tested in the ANOVA analysis.

Table 4.1: Results of ANOVA analysis where the difference between bloom and non-bloom situations on a number of variables is investigated. Significant differences are highlighted.

Variable	ANOVA effects			Difference bloom versus non-bloom
	Bloom	Station	Station* Bloom	
Salinity	<0.0001	0.0002	0.3687	0.73 psu
Salinity strat.	0.5976	<0.0001	0.0547	-0.17 psu
Temperature	0.1964	0.2919	0.0488	-1.06 °C
Temperature strat.	0.8288	<0.0001	0.1238	-0.68 °C
DIN	0.6218	<0.0001	0.0155	0.43 µmol/l
DIP	0.3956	<0.0001	0.5439	0.02 µmol/l
Dsi	0.0544	<0.0001	0.0001	0.55 µmol/l
Wind	0.0195	-	-	0.32 m/s
Wind (lag 1 day)	0.4706	-	-	0.10 m/s
Wind (lag 2 days)	0.0616	-	-	0.24 m/s
Wind (lag 3 days)	0.0049	-	-	0.37 m/s
Wind (lag 4 days)	0.0200	-	-	0.30 m/s
Wind (lag 5 days)	0.0003	-	-	0.49 m/s
Wind (lag 6 days)	0.0229	-	-	0.32 m/s
Wind (lag 7 days)	0.6895	-	-	0.06 m/s
Wind (lag 8 days)	0.0172	-	-	-0.35 m/s
Wind (lag 9 days)	0.3256	-	-	-0.13 m/s
Wind (lag 10 days)	0.3337	-	-	0.13 m/s

The bloom events identified above were combined with phytoplankton biomass data to identify the species that dominated the blooms. For this analysis there were only data available from the Danish national monitoring program. From the 233 bloom events identified by chlorophyll a observations, there were 46 simultaneous recordings of phytoplankton biomass by species. The dominating species by biomass are given in Table 4.2.



Table 4.2. Species dominating bloom events and the stations where the events were recorded.

Species group	Species identification	No. of blooms	Stations
<b>Cyanobacteria</b>	Anabaena sp.	1	190004
<b>Diatoms</b>	Rhizosolenia spp.	11	190004, 1939, 3310, 409, 925
	Leptocylindrus danicus	3	190004, 1993, 3310
	Skeletonema costatum	3	3310, 4410
	Cerataulina pelagica	1	1993
	Eupodiscales	1	4410
<b>Dinoflagellates</b>	Ceratium spp.	12	1001, 190004, 1939, 20004, 3310, 409, 413, 925
	Prorocentrum minimum	2	1993, 20004
	Dinophyceae, thekate	1	3310
	Gyrodinium aureolum	1	1001
	Heterocapsa triquetra	1	3310
<b>Others</b>	Ubestemte nanoplankton	7	1001, 409, 413, 925
	Cryptomonas sp.	1	190004
	Distephanus speculum	1	925

### 4.3 Discussion

The distributions of chlorophyll a in terms of both mean and extreme values have large spatial variations that need to be taken into account. The areas in Kattegat where high chlorophyll a concentrations are measured are close to major freshwater sources with high nutrient loading or in the frontal zone in the northern part, where Kattegat water mixes with high saline water from Skagerrak. The central southern part has the lowest concentrations and this area is dominated by Baltic Sea water.

The spatial distribution of frequency of blooms results in a different picture. Areas that are hydrographically active with high turbulent mixing have the highest frequency of blooms. These areas are the frontal zone in Northern Kattegat, the outflow areas in Southern Kattegat where Baltic Sea water is diverted through the Great Belt or the Sound.

The physical and chemical conditions before and during a bloom revealed that blooms occurred under higher salinity and wind conditions on 2-6 days prior to the observed bloom. Significant increases in DIN and DSi were also observed at a number of stations. This clearly indicates that the major cause of blooms occurring in Kattegat is due to mixing of nutrient-rich bottom water into the euphotic zone.

Finally, the blooms were dominated by diatoms and dinoflagellates species – mainly Rhizosolenia spp. and Ceratium spp. Ceratium is a species, which typically is observed around the pycnocline, but it can be mixed up into the euphotic zone and remain in the surface layer provided that nutrient conditions are favorable. The characteristics of the other species are less pronounced and do

not give any clear indications of the causes of the blooms. Thus, the phytoplankton composition also indicates that blooms are most likely due to wind-forced mixing of nutrient-rich bottom water into the surface layer.

## 5 Description and analysis of atmospheric data from Anholt

At Anholt the wet deposition is determined using bulk-collectors. The collectors are emptied twice every month and the sampled precipitation is analysed for its concentration of ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ). For a more detailed description of the samplers the reader is referred to Ellermann et al 1996.

Table 5.1 shows the monthly wet deposition at Anholt for the year 1999. The total deposition for the year 1999 was  $822 \text{ kg N/km}^2$ , with almost equal contributions from ammonium ( $\text{NH}_4^+$ ) and nitrate ( $\text{NO}_3^-$ ). The ammonium deposition amounted to  $394 \text{ kg N/km}^2$  and the nitrate deposition amounted to  $428 \text{ kg N/km}^2$ . The total precipitation collected at Anholt in 1999 was 782 mm.

*Table 5.1. Monthly wet deposition of nitrogen (the sum of ammonium and nitrate) at Anholt in 1999. Unit is  $\text{kg N/km}^2$ .*

January	60
February	40
March	119
April	69
May	69
June	87
July	45
August	74
September	105
October	53
November	30
December	71
Total	822

The amount of precipitation at Anholt varies a lot on a monthly scale, as can be seen in Figure 5.1. Despite the great variations there is a tendency for the amount of precipitation to be greater in autumn and winter and minor during summer. The monthly variations in nitrate and ammonium measured at Anholt also shows great variations, as can be seen in Figure 5.2 (ammonium) and Figure 5.3 (nitrate). When analysing the data it turns out, that there is no clear seasonal variation in the wet deposition of nitrate. The wet deposition of ammonium is in general greater during the summer period despite the lower precipitation amounts in the summer period (Cappelen *et. al.* 2000). This greater deposition is probably due to larger air concentrations of ammonia ( $\text{NH}_3$ ) in the summer period. These high ammonia concentrations are mostly due to the high emissions of ammonia from the Danish agricultural land areas.

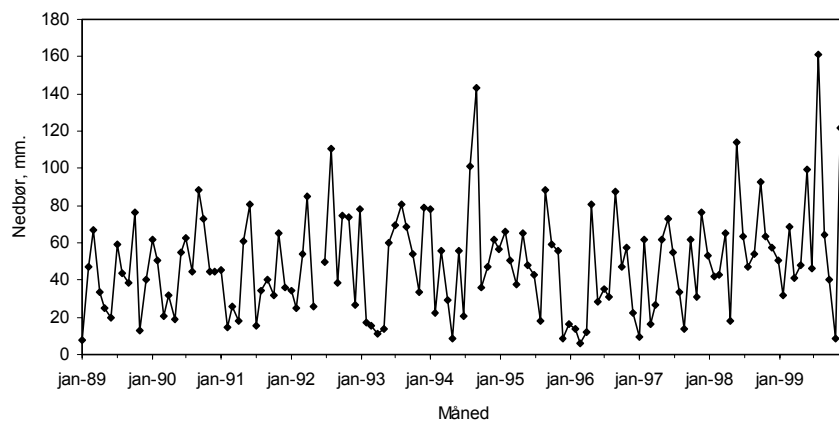


Figure 5.1. Monthly precipitation measured by NERI at Anholt during the period 1989-1999.

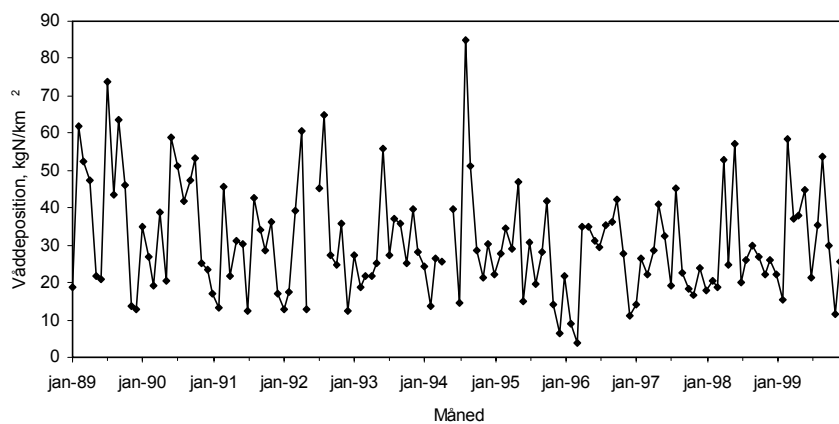


Figure 5.2. Monthly wet deposition of ammonium measured by NERI at Anholt in the period 1989 to 1999.

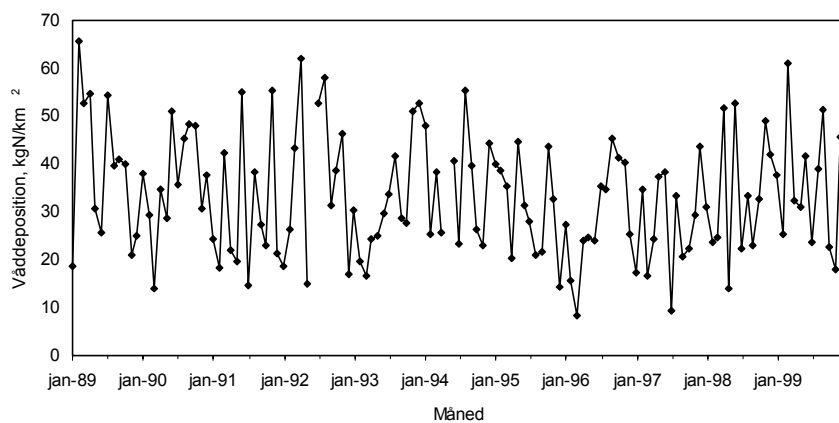


Figure 5.3. Monthly wet deposition of nitrate measured by NERI at Anholt in the period 1989 to 1999.

Comparing Figures 5.1-5.3 the monthly wet deposition can be seen to follow the changes in precipitation to some extent. The precipitation is the main controlling factor of the wet deposition, but other factors also play a role. The precipitation measurements made by NERI have been compared to gridded values obtained from The Danish Meteorological Institute for the year 1999. The agreement between the measurements made by NERI and the gridded values from DMI is found to be satisfying, taking into account the error introduced by comparing point measurements with gridded values.

Throughout the whole period 1989-1999 a small decrease in the measured wet deposition can be observed, however, analysis of this decrease shows it not to be statistically significant. The deposition decrease is most likely to be caused by a decrease in ammonia emissions in Denmark and surrounding countries.

## 6 Atmospheric deposition of nitrogen to the Kattegat Sea

### 6.1 Method

The deposition of nitrogen to Kattegat has been estimated using a transport chemistry model – the ACDEP model (Atmospheric Chemistry and Deposition model). ACDEP is a trajectory model, in which air parcels are transported along 96 hours trajectories to a given net of receptor points. 10 layers in a vertical column from the surface and up to 2 km's height represent the air parcels. During the transport the air parcels receive emissions and processes like vertical diffusion, chemical transformation and dry and wet deposition take place, see Figure 6.1.

The chemical mechanism of the model includes 37 species and about 80 reactions. For details on the model structure and the parameterisations in the model, see (Hertel *et al.* 1995). The results from the ACDEP calculations used in the MEAD project are the results calculated for the Danish Background Monitoring Programme in order to provide information regarding the spatial distribution of the nitrogen deposition to Danish marine waters, see Ellermann *et al.* 2000. The model calculations have been performed for receptor points covering the Danish marine waters as well as the Swedish part of Kattegat and Øresund. The grid resolution is 30 km x 30 km and calculations are available for the years 1989 to 1999

The nitrogen components in the model include NO, NO<sub>2</sub>, PAN, NH<sub>3</sub>, NH<sub>4</sub>NO<sub>3</sub>, NO<sub>3</sub>, N<sub>2</sub>O<sub>5</sub>, HNO<sub>3</sub>, HNO<sub>2</sub>, HNO<sub>4</sub>, NH<sub>4</sub>HSO<sub>4</sub>, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> as well as other (less important) organic and inorganic nitrates. The total nitrogen depositions to Kattegat used in the MEAD project are based on the sum of the above nitrogen components.

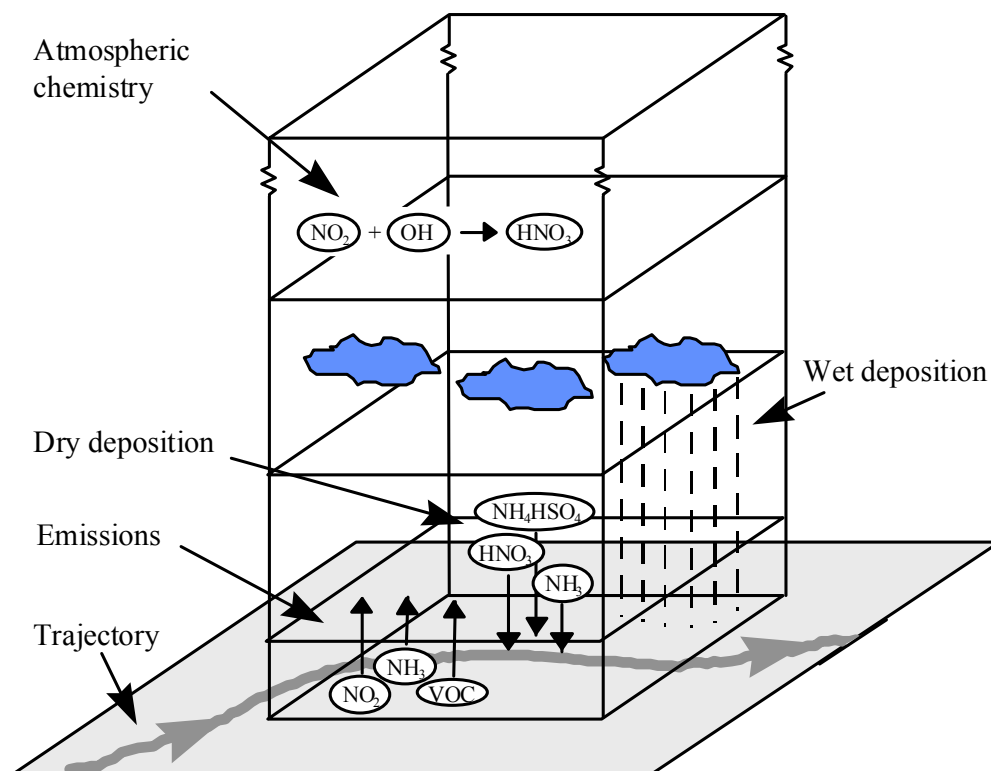


Figure 6.1. Illustration of the ACDEP modelling concept. A one dimensional vertical air column is advected along 96 hour back-trajectories. During the advection, the column receives emissions, vertical mixing takes place, species are chemically transformed and/or removed by dry and wet deposition.

Approximately 70 % of the deposition consist of wet deposition of highly episodic nature. Therefore the accuracy of the precipitation data is critical for the accuracy of the resulting depositions. For the period 1989 to 1998 precipitation data have been obtained from EMEP MSC-W (European Monitoring and Evaluation Programme, Meteorological Synthesizing Centre – West) on a 150 km x 150 km grid. The data were kindly provided by Helge Styve, Hilde Sandnes and Egil Støren. The rather coarse resolution in these data makes it difficult to accurately determine the spatial extent as well as the duration of rain events.

For the year 1999 precipitation data have been obtained from calculations with the Eta model, (Nickovic et al, 1998) currently run operationally at NERI, (Brandt *et al.* 2000). The Eta data have a spatial and temporal resolution, which is 6 times higher than the resolution in the EMEP data. The Eta precipitation data seems to be in good agreement with measurements for the whole of Denmark (see Scharling, 1998 for details on the measurement data), as can be seen in Figure 6.2, showing the calculated and measured accumulated precipitation for the year 1999.

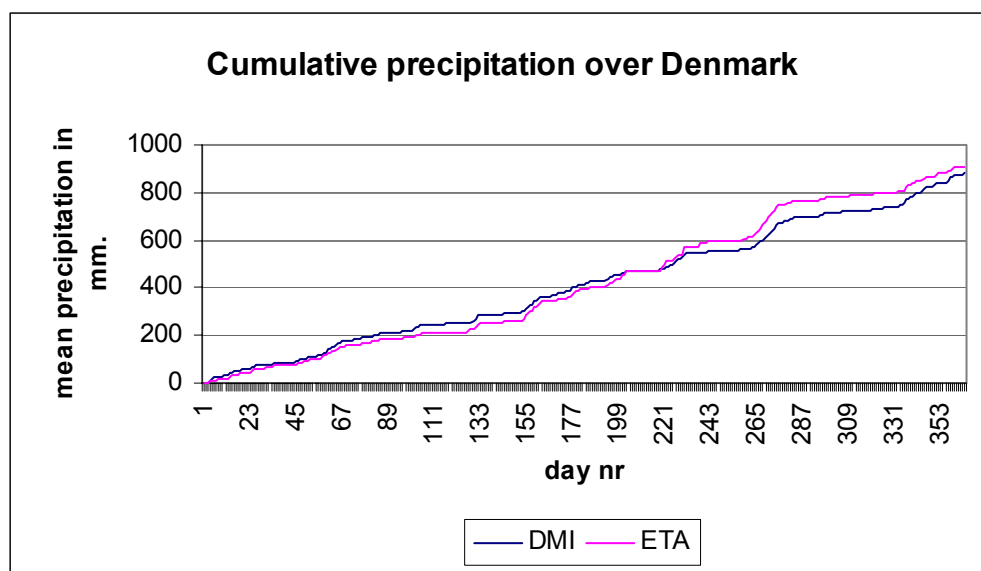


Figure 6.2. Accumulated precipitation, comparison of precipitation calculated with the Eta model and precipitation measured by The Danish Meteorological Institute.

## 6.2 Results

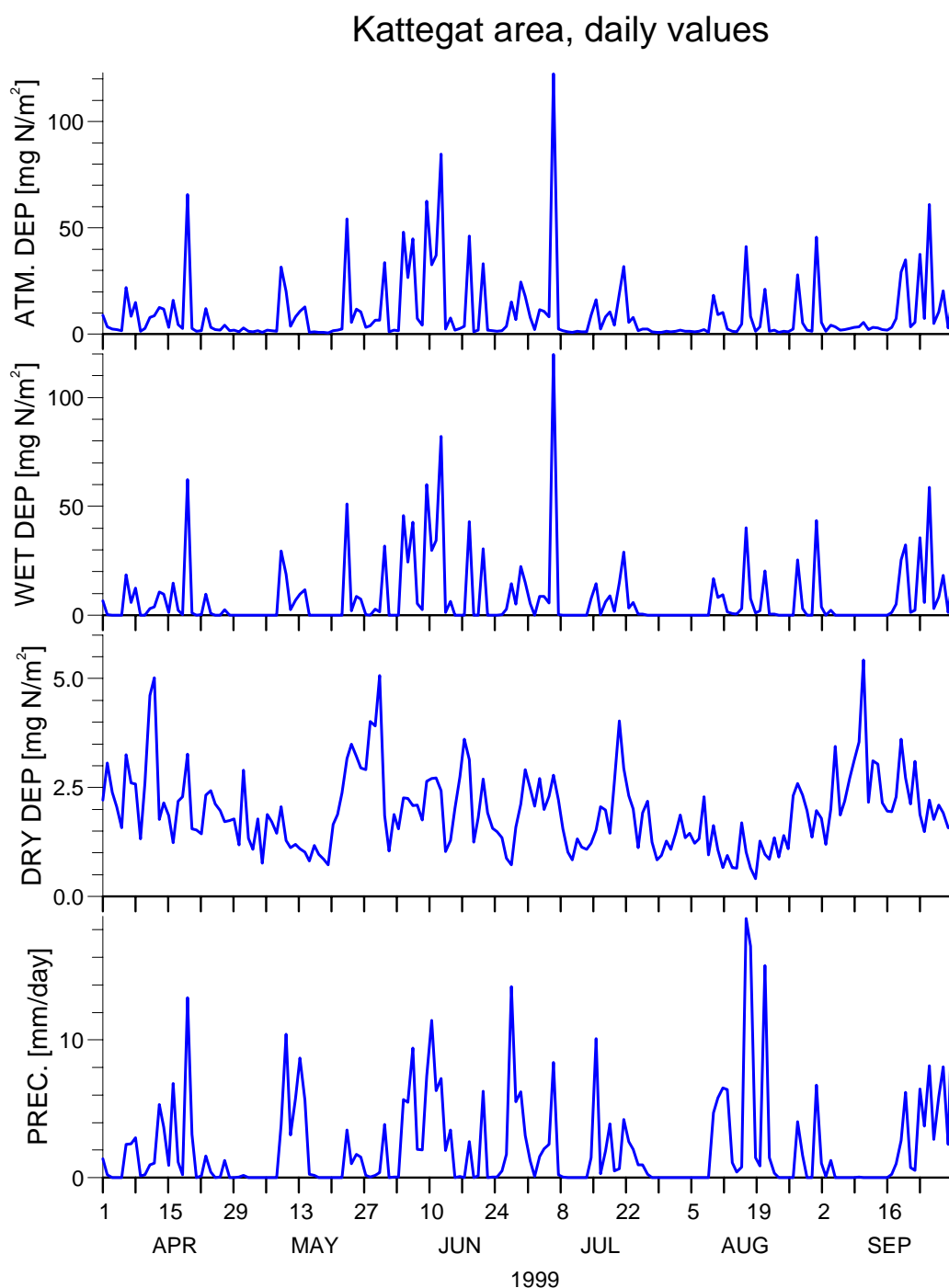
The daily deposition values for Kattegat for the year 1999 can be seen in Figure 6.3 and 6.4. Figure 6.3 shows values for the period of main interest to the MEAD project, namely the period from April to September. Figure 6.4 shows the daily deposition for all of 1999. The unit of deposition is  $\text{mg N/m}^2$  and the total area of Kattegat (Danish and Swedish) is taken to be 23,583  $\text{km}^2$  (based in information from the Geological Survey of Denmark and Greenland). There are 4 panels in the figures, the top panel giving the total atmospheric deposition, second the wet deposition, third the dry deposition and fourth the precipitation on a daily basis.

Extracting daily values from model calculations of this kind is pushing the ACDEP model close to its limit. This is especially due to the difficulties with the accurate determination of clouds and rain events. In order to increase the reliability in the use of the data, the accumulated values over the year or period of interest can be used instead of the daily values. The accumulated deposition for April to September 1999 is shown in Fig. 6.5 and for the whole year Fig. 6.6.

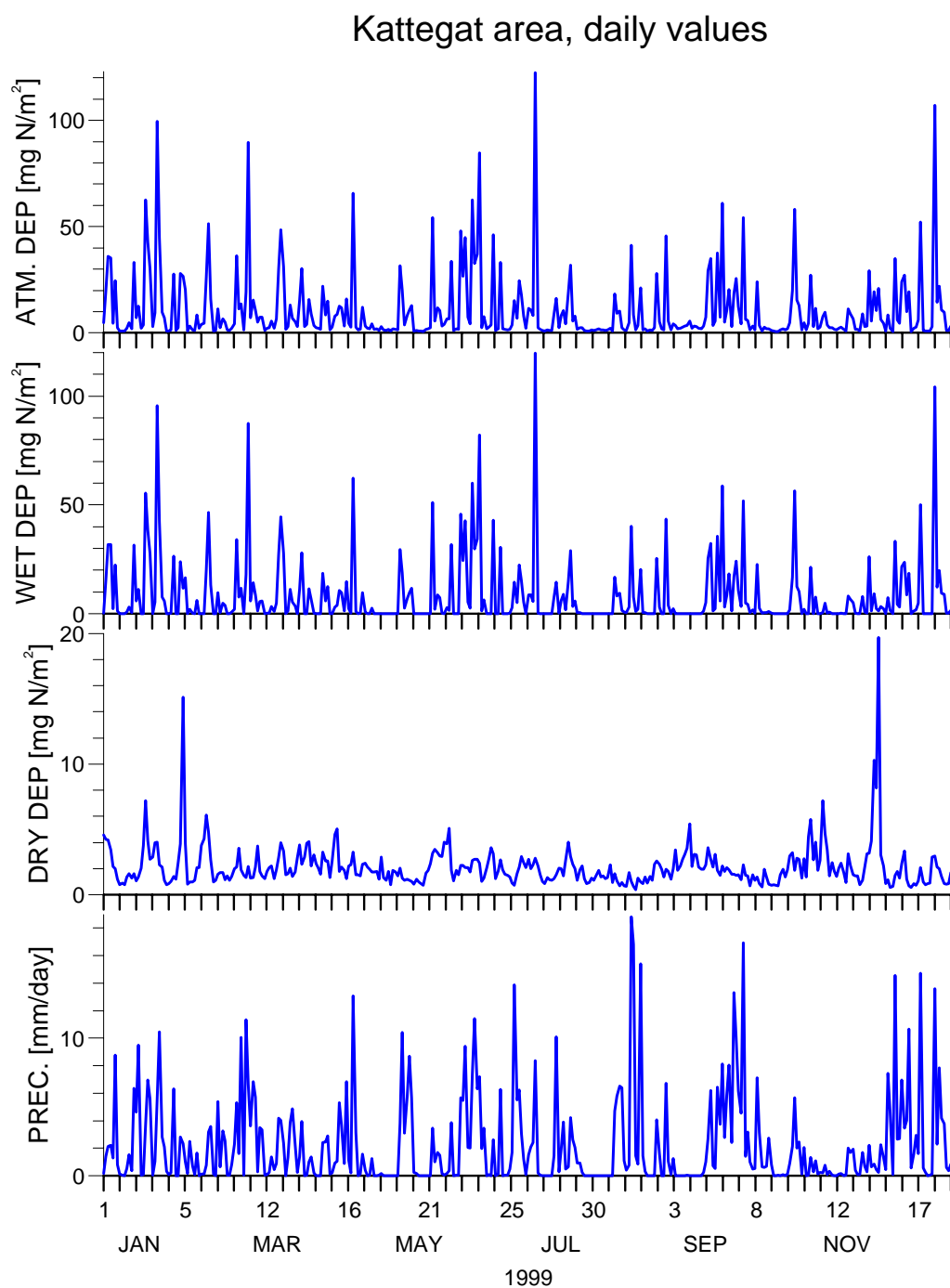
As can be seen the atmospheric dry deposition is an order of magnitude smaller than the wet deposition on a daily scale and about a quarter smaller as accumulated values. The accumulated fluxes of nitrogen into the marine surface layer from the atmosphere have been compared to the accumulated fluxes from the deep water calculated with the marine model in order to determine where the majority of nutrients comes from in different periods.

Daily values of atmospheric nitrogen deposition calculated with the ACDEP model together with daily values of the nitrogen flux from the bottom waters calculated by a hydrodynamic model are shown in odd numbered figures (Figs. I-XXI in appendix F) for the period 1989-1999 (April – September). Top panel

is total atmospheric deposition, second is atmospheric wet deposition, third is the nitrogen flux from the bottom waters to the marine surface layer and fourth is the precipitation on a daily basis. Furthermore the accumulated values of deposition and bottom water flux can be seen in even-numbered figures (Figs. II-XXII in appendix F).



*Figure 6.3. Daily values of total, wet and dry deposition of nitrogen as calculated with the ACDEP model and precipitation for the period April-September 1999*



*Figure 6.4. Daily values of total, wet and dry deposition of nitrogen as calculated with the ACDEP model and precipitation for the period January – December 1999.*



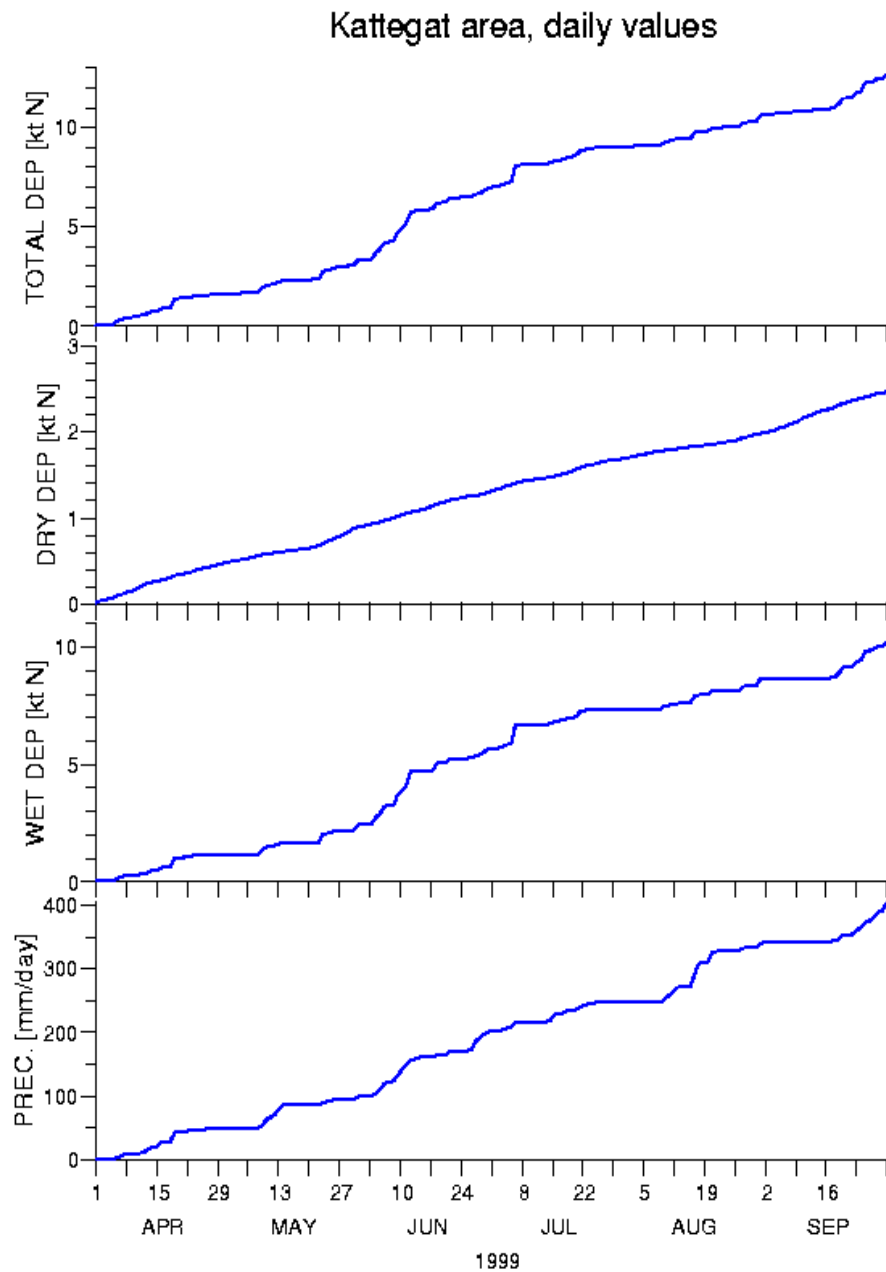


Figure 6.5. Accumulated values of atmospheric total, dry and wet nitrogen deposition as calculated with the ACDEP model and precipitation for the period April - September 1999.

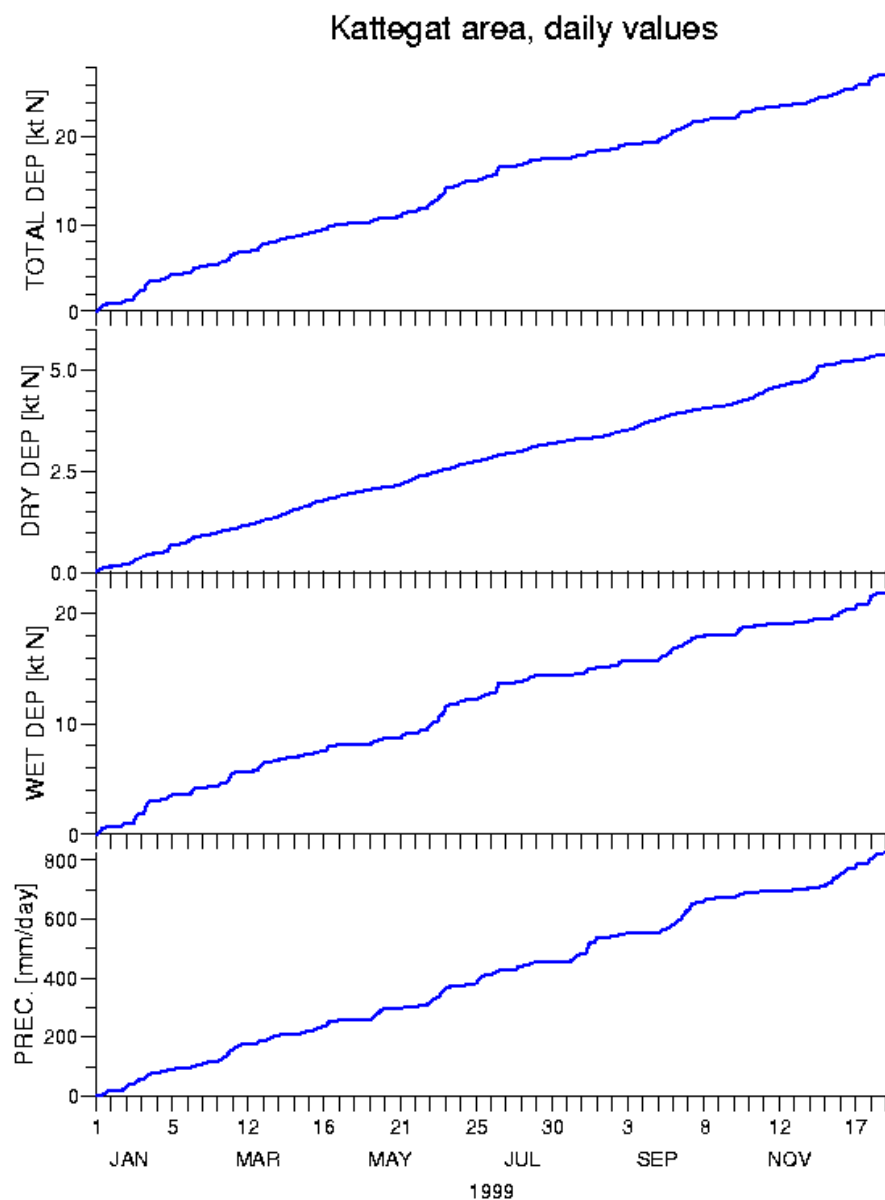


Figure 6.6. Accumulated values of atmospheric deposition of total, dry and wet nitrogen deposition as calculated with the ACDEP model and precipitation for the period Januar-December 1999.

### 6.3 Discussion

The deposition of nitrogen to the Kattegat area has been calculated with the atmospheric transport-chemistry model ACDEP. The resolution of the data is 30 km \* 30 km and data are available for the years 1989 to 1999. All inorganic components relevant for atmospheric deposition are included in the model. Approximately 70 % of the deposition consists of wet deposition of highly episodic nature. For this reason the deposition results depend crucially on the data available to describe the precipitation. For the period 1989-1998 the available precipitation data have a rather coarse resolution that makes it difficult to accurately quantify the spatial and temporal distribution of the rain events.

For the year 1999 precipitation data with 6 times higher spatial and temporal resolution have been available, thus providing much better estimates of wet deposition for this particular year. The results are presented as time series of total deposition and wet deposition together with nitrogen fluxes from the bottom waters to the surface layer calculated with the hydrodynamic model (see section 7). The atmospheric deposition of nitrogen is in the same order of magnitude as the flux from the bottom waters.

## **7 Estimation of nutrient flux events from wind forced entrainment of deep-water in Kattegat**

### **7.1 Method**

A basin-scale hydrodynamic model has been used to estimate the flux of nutrients to the mixed layer by wind forced entrainment. The hydrodynamic model resolves the Kattegat horizontally with three sub-basins and in the vertical with 50 layers (see Fig. 7.1). The model also covers the remaining of the Baltic Entrance Area and the Baltic Sea. The mixed layer dynamics is parameterized with a bulk approach. The details of the model are given in Gustafsson (2000).

The main focus of this calculation is to estimate the magnitude and frequency of mixing events that can feed the mixed layer with nutrients from below. The methodology is to use observed salinity-nutrient relations with monthly resolution together with the modeled entrainment rate to estimate the nutrient flux. However, decreasing wind speeds and/or increasing buoyancy flux due to heating or freshwater supply can lower the turbulent kinetic energy in the mixed layer. That causes the mixed layer thickness to decrease. During variable weather conditions the mixed layer thickness can increase and decrease frequently without substantial upward transport of deep-water.

When the wind speed increase and/or the buoyancy supply ceases, the erosion will start by entraining water that rather recently was within the mixed layer. Especially during summer, this water will be rather depleted of nutrients and not give a substantial increase of nutrients to the mixed layer. Thus, we need to separate between entrainment of old mixed layer water and nutrient rich deep-water. In principle, this would be done by the use of salinity-nutrient relations, but as the salinity difference may be small and further model errors may be comparatively large it is not practical.

Instead we also introduce an artificial tracer in the model that has the concentration equals to 1 in the Skagerrak water that feeds the deep-water of Kattegat and the concentration is set to 0 in the surface mixed layer. Thereby we have a weight factor that can be used to estimate the entrainment of nutrient rich deep-water.

The entrainment flux is calculated by at each time-step, first estimating a nutrient concentration profile in the model from the salinity-nutrient relation for that month and then sum up the entrainment of nutrients using:

$$F = \int_t^{t+\Delta t} w_E C_N C_W dt$$

where  $w_E$  is the entrainment rate,  $C_N$  nutrient concentration and  $C_W$  the concentration of the tracer that approximates the relative amount of deep-water. The nutrient fluxes calculated in this way will probably not give the total upwelling of nutrients in Kattegat, but the resulting time-series represent an order of magnitude estimate of the entrainment fluxes and their frequency.

## 7.2 Results

The calculations were done for the period 1976-1999 with the observed salinity-nutrient relations from Rasmussen and Gustafsson (2003). The resulting nutrient flux time-series are shown in Fig. 7.2, for Southern and Central Kattegat. The fluxes appear to be somewhat higher in Southern than in Central Kattegat, mainly because the results are presented as average over surface area and there are larger shallow areas in Central Kattegat that often are above halocline depth. Maximal fluxes of DIN (DIP) reach values as high as 600 (100)  $\text{mg N m}^{-2} \text{ day}^{-1}$ .

These events are only of significance during the productive season when the surface layers are depleted of nutrients. Therefore it is more relevant to consider the period May-August. In Fig. 7.3, the cumulative distributions of events of nitrogen entrainment flux within the summer period are drawn for Southern and Central Kattegat.

We see that major events are quite rare, there are about 10 days with a flux higher than 80  $\text{mg N m}^{-2} \text{ day}^{-1}$  and about 100 days with flux higher than 20  $\text{mg N m}^{-2} \text{ day}^{-1}$  in Central Kattegat. If all nitrogen is bound into organic carbon with a Redfield ratio of 5.7, these fluxes correspond to a production increase of 446 (114)  $\text{mgC m}^{-2} \text{ day}^{-1}$ . Assuming a typical mixed layer depth of 10 m an increase in biomass of some 45 (11)  $\text{mgC m}^{-3} \text{ day}^{-1}$  could be expected.

Close-ups on the entrainment flux of DIN during the summers of 1987 to 1991 are shown in Fig. 7.4. We see that the number of significant events differ substantially between the summers. However, the actual magnitude of an event does not necessarily have the duration of one day, therefore graphs of the time-integrated flux are more appropriate. In Fig. 7.5, the time-integrated DIN flux is shown for three consecutive summers without data gaps. We see that the total flux during the summer differs by a factor of more than 4 between 1989 and 1990.

Figures showing both the atmospheric and the marine in-flux to the upper ocean Kattegat Sea are graphed Fig 6.7-6.27 (odd numbers). The graphs show the summer periods April to September for the years 1989 to 1999. The cumulative values of atmospheric deposition and deep water flux is shown as well as the precipitation with a daily resolution (Fig 6.8-6.28 (even numbers)).

It can be noted that the axis are the same, hence the event are of the same order of magnitude. Yet the cumulative atmospheric deposition is always larger than the marine deep water flux.

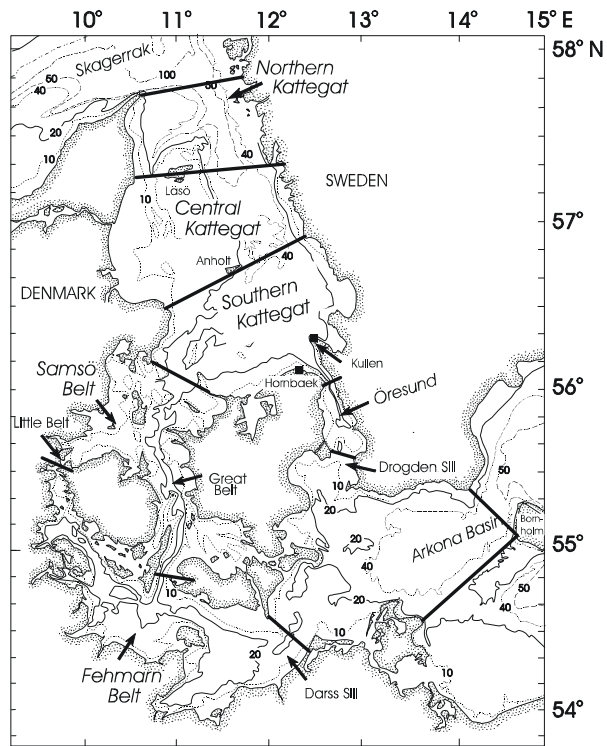


Figure 7.1. Map of the Kattegat-Belt Sea showing the model sub-basin partitioning.

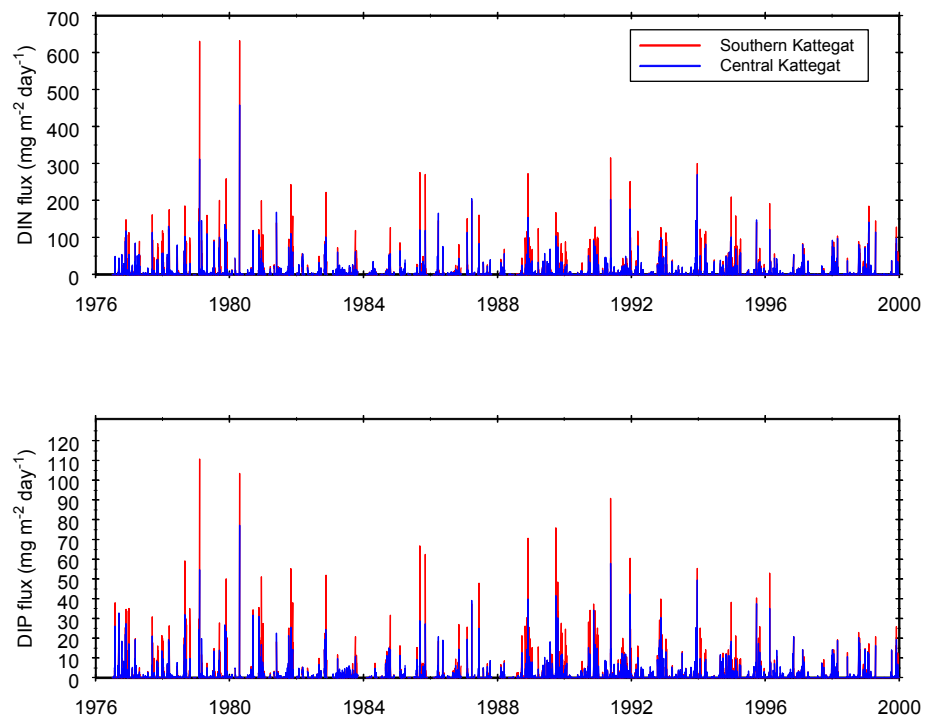


Figure 7.2. Entrainment flux events of DIN (upper panel) and DIP (lower panel). There are some gaps in the time-series due to lack of observational data.

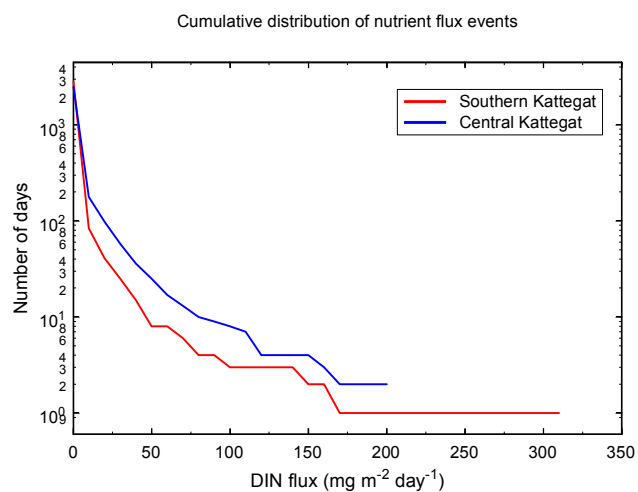


Figure 7.3. Cumulative distribution of nitrogen (DIN) fluxes during summer for the two sub-basins Southern and Central Kattegat. In total, there are some 2700 days of data.

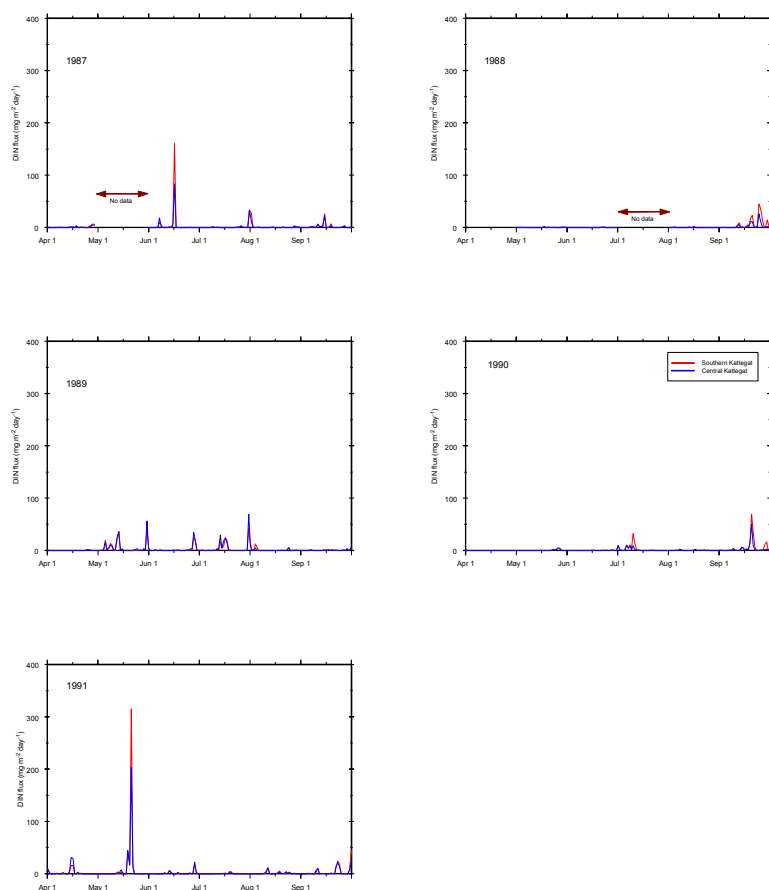


Figure 7.4. Entrainment fluxes of DIN for the summers between 1987 and 1991.

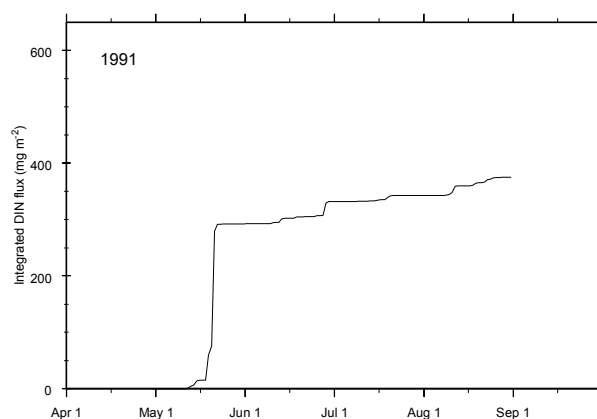
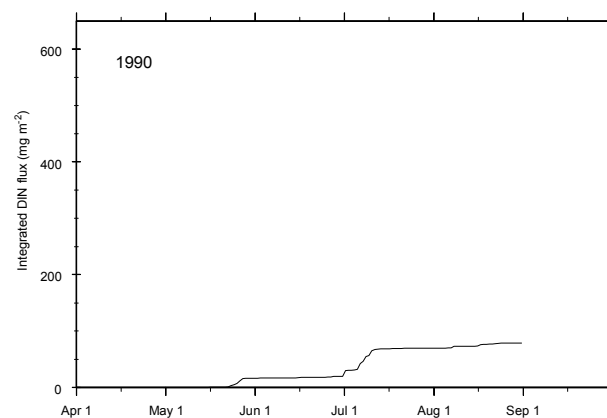
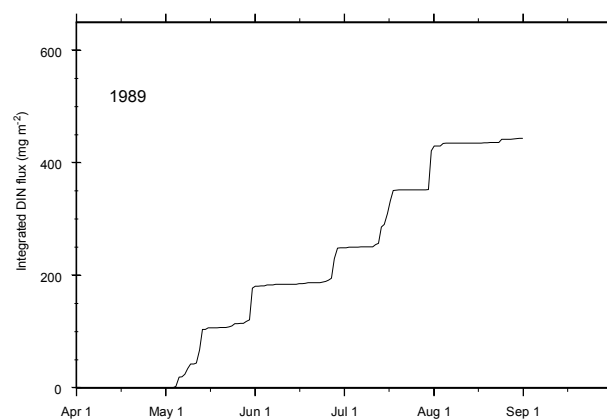


Figure 7.5. Integrated DIN fluxes for Central Kattegat during three summers. The integration starts on May 1 each year.

## 8 Satellite data

### 8.1 Description of satellite data

Optical sensors on-board satellites provide data on the state of the sea surface. From the visible bands - including blue – quantitative estimates on marine chlorophyll and ocean colour content can be retrieved (e.g. Stewart, 1985). From the thermal bands the sea surface temperature is calculated. Images from CZCS (Coastal Zone Color Scanner) flown on satellite NIMBUS-7 are the first satellite data collected focussing on the marine environment, yet this sensor fell silent in mid-1986 (Kramer, 1996), hence no data are available for the early 1990'ties.

A blue-band sensor was planned for Landsat-6. Unfortunately it never came into orbit, hence only when SeaWiFS (Sea Wide Field Sensor) in september 1997 came into orbit, has an archive with emphasis on ocean colour been collected. NOAA AVHRR (National Oceanic and Atmospheric Administration, Advanced Very-High Resolution Radiometer) and Landsat TM (Thematic Mapper) data cover the last decade, yet the retrieved information is sea surface temperature (SST) and therefore provide only an indirect and qualitative measure of algae blooms.

In the Kattegat area a toxic algal bloom (*Chrysochomulina polylepis*) occurred in May-June 1988 as mapped by AVHRR thermal bands (Dundas *et al.* 1989, Johannessen *et al.* 89, Hansen *et al.* 1993 p 34). In the areas with high concentrations of algae, the SST was higher than normal. On 27 May 1988 this occurred in the northeastern part of Kattegat/Skagerrak and in the fjord of Oslo.

Further NOAA AVHRR SST weekly and monthly maps provide quick and reliable overviews of the environmental conditions. E.g. one can see if a certain period was colder or warmer than average and the spatial variability. Such maps are produced for the period from January 1990 to present (Roozkrans, 1999).

In Table 8.1 is listed some names of satellites and sensors, years of launch, spatial resolution and number of bands. Several new sensors such as MODIS (Moderate Resolution Imaging Spectroradiometer), MISR (Multi-angle Imaging Spectro-Radiometer) and MERIS (MEdium Resolution Imaging Spectrometer) will provide imagery of ocean colour in the coming years. Further information is available at IOCCG (International Ocean Colour Coordinating Group <http://www.ioccg.org/sensors/500m.html#2>).

*Table 8.1. List of optical satellite sensors available in the 1990'ties for ocean parameter mapping.*

Satellite	Sensor	Year	Pixel	bands
Landsat	TM	1986-	30 m	7
NOAA	AVHRR	1989-	1 km	5
SeaStar	SeaWiFS	Sep. 1997-	1.12 km	8
Terra Aqua	MODIS	Dec. 1999-	250, 500, 1000 m	36
Terra	MISR	Feb. 2000 -	1.1 km	4
ENVISAT	MERIS	Jun. 2001	300 m/1.2 km	15



Satellite data from the various sensors have been calibrated and analysed in numerous laboratories. Processed data on the global sea surface temperature (SST) are archived in the NASA Pathfinder archives. At <http://podaac.jpl.nasa.gov> globally gridded products are available e.g. a 9 km resolution at a daily time scale spanning jan. 1987 to nov. 1999. Raw NOAA AVHRR data from northern Europe are archived at <http://www.sat.dundee.ac.uk> and quicklooks are available from nov. 1978 to present, though with some gaps.

In parallel to the optical satellite imagery, satellite microwave scatterometer data are available from the last decade. Scatterometer data provides maps of ocean wind speed and direction. Table 8.2 gives a listing of the satellites, sensors and years of operation. The acronyms are: ERS (European Resource Satellite), SCAT (scatterometer), ADEOS (Advanced Earth Observation Satellite), NSCAT (NASA's scatterometer) and QuikSCAT (Quick Scatterometer).

*Table 8.2. List of scatterometer sensors available in the 1990'ties for ocean wind speed and direction.*

Satellite	Sensor	Year
ERS-1	SCAT	August 1991- May 1996
ERS-2	SCAT	April 1995-
ADEOS	NSCAT	September 1996-June 1997
QuikSCAT ADEOS II	SeaWinds	July 1999-

The scatterometer data are available e.g. through <http://www.ifremer.fr/cersat> collocated database as weekly and monthly values at a 1° by 1° spatial averaging grid.

Further is available SSM/I (Special Sensor Microwave/Image) with passive microwave radiometers providing ocean wind speed through the measurement of the brightness temperature since August 1991.

In the future (year 2005) SMOS (Soil Moisture and Ocean Salinity) from ESA will provide maps of ocean salinity through radar techniques (Font *et al.* 2000). Ocean colour missions 1978-2010 and beyond is described in Gregg and McClain (2001) and it is clear that an increase in relevant data is foreseen.

Near-real time mapping of chlorophyll levels and algal blooms in the North-Sea/Skagerrak using ocean colour data (SeaWIFS) and NOAA AVHRR is performed in Norway at the Nansen Environmental Remote Sensing Centre in the project DeCiDe (<http://www.nersc.no/~domi/HAB/enter.html>). Maps of chlorophyll levels are available daily including the Kattegat Sea.

For the Danish waters SeaWIFS data have been analysed and compared to in-situ chlorophyll data by Jørgensen and Alvarez-Berastegui (2000) and to results derived from the 3-dimensional hydrodynamic model "Farvandsmodel" (Edelvang *et al.* 2001). The satellite data analysis was based on 47 SeaWIFS scenes from 1999. Results show that the standard SeaWIFS algorithm for chlorophyll is not accurate primarily due to inaccurate atmospheric correction in coastal and turbid waters, but also due to relatively high and variable abundance of yellow

substance. But other new algorithms are better and the results compare favourably to hydrodynamic model results.

## 8.2 SeaWiFS

Seven SeaWiFS scenes are analysed in the current study. The requirement from NASA on chlorophyll a ( $C_a$ ) mapping accuracy is 35% but this has been difficult to fully meet with the OC2 algorithm especially in case 2 water (O'Reilley et al, 1989). The newest operational algorithm, OC4v4 (O'Reilley et al, 2002) seems to be able to meet the NASA requirement criteria for case 1 and case 2 waters. Case 1 is oligotrophic and case 2 eutrophic waters. The Kattegat Sea is case 2 water. The OC4v4 algorithm is based on 4 channels whereas the OC2 algorithm is based on only two channels. The OC4v4 algorithm is

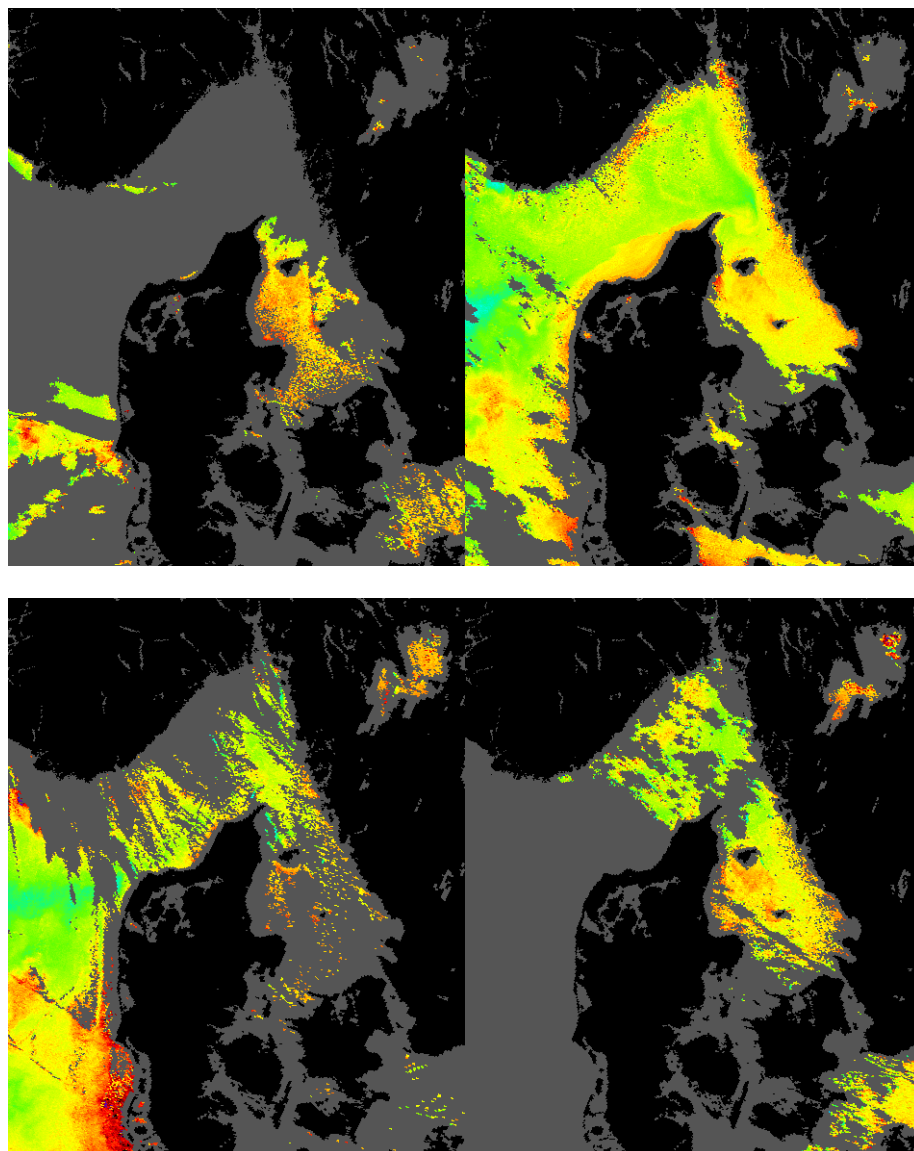
$$C_a = 10.0^{0.366 - 3.067 R_4 + 1.930 R_4^2 + 1.532 R_4^4} \quad (\text{Eq. 8.1})$$

where

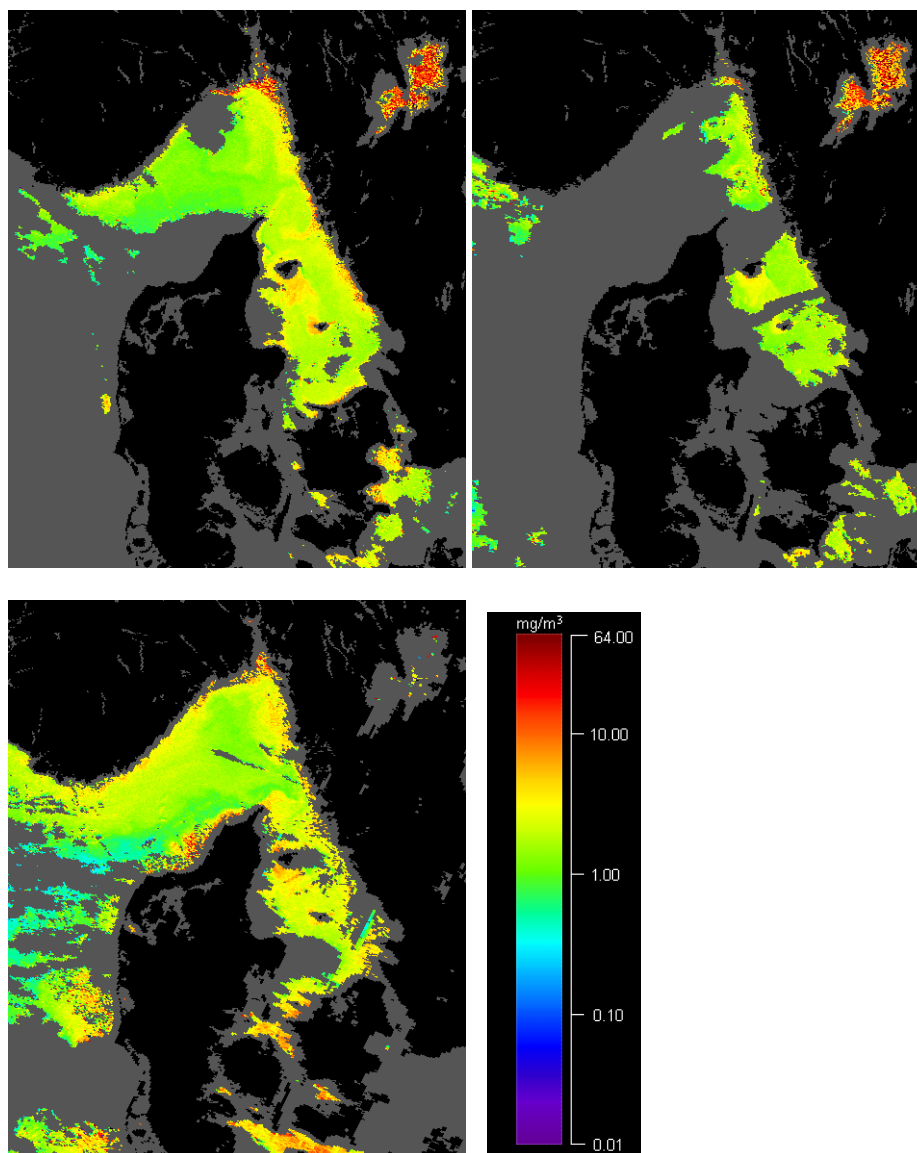
$$R_4 = \log_{10}(R_{555}^{443} > R_{555}^{490} > R_{555}^{510}). \quad (\text{Eq.8.2})$$

$C_a$  is the chlorophyll a concentration ( $\text{mg m}^{-3}$ ).  $R_4$  is the reflectance determined from four optical bands. The bands are 20 nm wide and are centered at the four wavelength,  $\lambda$ , at 443 nm (blue), 490 nm blue-green), 510 nm (green) and 555 nm (green) and  $R_{\lambda_1}^{\lambda_2}$  is the reflectance band ratio between the wavelength,  $\lambda_1$  and  $\lambda_2$ . The band ratio  $R_{555}^{490}$  is the best overall single band ratio index on  $C_a$  concentration, but because  $R_{555}^{443}$  is superior in oligotrophic waters and  $R_{555}^{510}$  is superior in eutrophic water, the so-called maximum band ratio is used in the polynomial function (Eq. 8-1). In other words, the OC4v4 algorithm takes advantage of the band-related shift in precision that is a function of the well-known shift of the maximum  $R(\lambda)$  spectra towards higher wavelengths with increasing  $C_a$  (O'Reilley et al., 2002). Recently, Joergensen (2003) has successfully compared SeaWiFS OC4v4  $C_a$  data to  $C_a$  in-situ observations for a limited data set consisting of 30 match-up's in the Danish waters.

Seven  $C_a$ -maps from SeaWiFS satellite scenes retrieved by the OC4v4 algorithm (eqs. 8.1-8.2) are compared to in-situ  $C_a$  observations from a buoy and the ScanFish in the Kattegat Sea. The SeaWiFS chlorophyll maps are shown in Figure 8-1 and Figure 8-2.



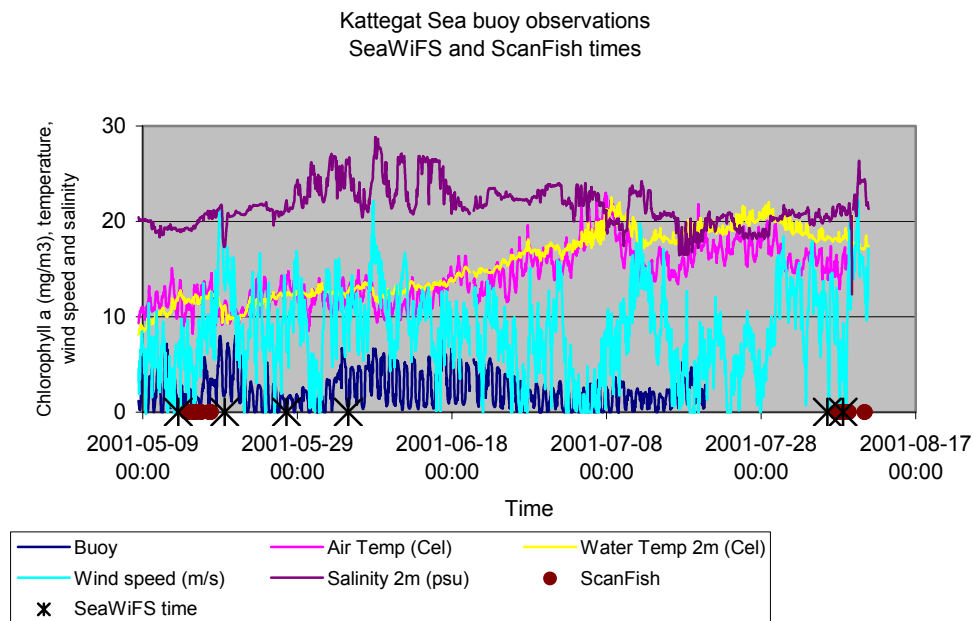
*Figure 8-1 Chlorophyll a maps derived from SeaWiFS by the OC4v4 algorithm for the Danish waters: upper left 13 May 2001, upper right 19 May 2001, lower left 25 May 2001 and lower right 27 May 2001. Please see the colour legend in Figure 8-2.*



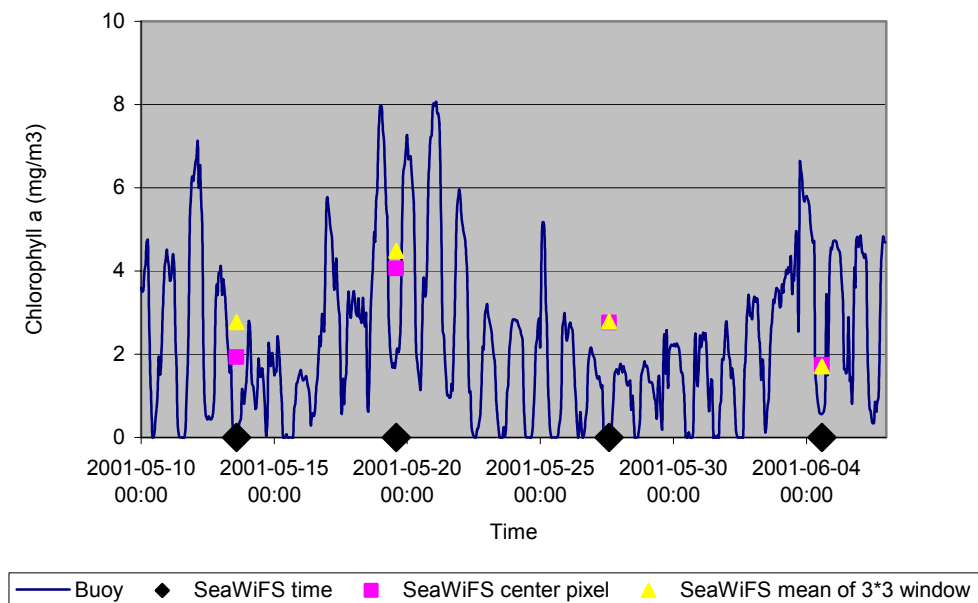
*Figure 8-2 Chlorophyll a maps derived from SeaWiFS by the OC4v4 algorithm for the Danish waters: upper left 4 June 2001, upper right 5 August 2001 and lower left 7 August 2001.*

An overview of the available in-situ observations during time of the SeaWiFS scenes is given in Figure 8-3. It is seen that the buoy  $C_a$  observations discontinue medio July. Four of the SeaWiFS scenes are compared to the buoy observations and one scene to the ScanFish observations.

Comparison of the  $C_a$  values from the buoy and SeaWiFS is shown in Figure 8-4 and listed in Table 8-1. It is clear that the values are rather different which is surprising as the observations are collected very closely in time (less than  $\pm 30$  minute). The buoy observations on  $C_a$  vary greatly at a diurnal time scale from from  $8 \text{ mg m}^{-3}$  in the night to less than  $2 \text{ mg m}^{-3}$  during the following day measured at a depth of  $-2 \text{ m}$ .



*Figure 8-3 Observations at an hourly time scale from the buoy in the Kattegat Sea of chlorophyll a, water temperature and salinity at –2 m depth and air temperature and wind speed at 2 m height. The times of ScanFish cruises and SeaWiFS satellite scenes are indicated.*



*Figure 8-4 Chlorophyll a concentration observed at a buoy in the Kattegat Sea per hour and observed by the SeaWiFS satellite showing the values from the center pixel and average of a 3 by 3 window.*

All SeaWiFS scenes are recorded around an hour after local noon. The spatial variation in  $C_a$  from SeaWiFS is moderate in four cases ( $\approx 0.4 \text{ mg m}^{-3}$  standard deviation) but high ( $\approx 0.7 \text{ mg m}^{-3}$ ) in the local area around the position of the buoy (Table 8-1). This local variation however does not indicate any values in the range of the buoy. The buoy is moored at more than  $\sim 70 \text{ m}$  water depth, hence limitations of SeaWiFS related to shallow waters ( $<10 \text{ m}$  water depth) does not explain the relatively high  $C_a$  values found in SeaWiFS.

*Table 8-1 SeaWiFS chlorophyll  $a$  ( $\text{mg m}^{-3}$ ) values from the center pixel and the mean, minimum, maximum and standard deviation from a 3 by 3 window centered at the buoy.*

	Buoy	Center	Mean	Min.	Max.	Std.dev.	Pixels
20010513	0.0	1.9	2.8	1.9	4.0	0.7	9
20000519	1.9	4.1	4.5	3.3	6.1	0.8	9
20010527	0.0	2.8	2.8	2.3	3.5	0.4	9
20010604	0.6	1.7	1.7	1.5	1.9	0.2	9
20010805	n.a.	1.5	1.5	1.4	1.5	0.1	9
20010807	n.a.	2.4	2.1	1.4	2.4	0.4	5*

\* the other pixels are cloud covered

A series of ScanFish observations were collected during several experimental cruises and all the shiptracks for the period in early August 2001 are shown in Figure 8-5. The ScanFish is an undulating wing dragged after a ship and from this the ScanFish observations of  $C_a$  are obtained (Johnsson, 2002). The ScanFish data are retrieved by a fluorometer (WETLABS, WETStar Miniature Fluorometer) and the fluorescence detected is calculated into  $C_a$  from the following relationship

$$Fl = 2.439C_a - 2.143 \quad (\text{Eq.8-3})$$

with  $Fl$  fluorescence ( $\text{mg m}^{-3}$ ) and  $C_a$  ( $\text{mg m}^{-3}$ ). (Stiig Markager, pers.com.)

The  $C_a$  levels are recorded in transects up to 32 km long and down to 70 m water depth. In the current study however, only the surface layer is investigated and  $C_a$  is averaged over the top 5 m of the surface layer. It may be noted that the ScanFish sampling only took place at areas characterized by relatively deep water ( $> 40 \text{ m}$  depth).

The map of  $C_a$  from SeaWiFS recorded on August 7<sup>th</sup>, 2001 at 12.55 UTC is shown in Figure 8-2. During this day, four ScanFish tracks were collected (number 2, 3, 4 and 5 in Figure 8-5) and the values of  $C_a$  from the upper 5 m over the mixed surface layer are averaged along the horizontal transects and compared to the SeaWiFS observations in Figure 8-6.

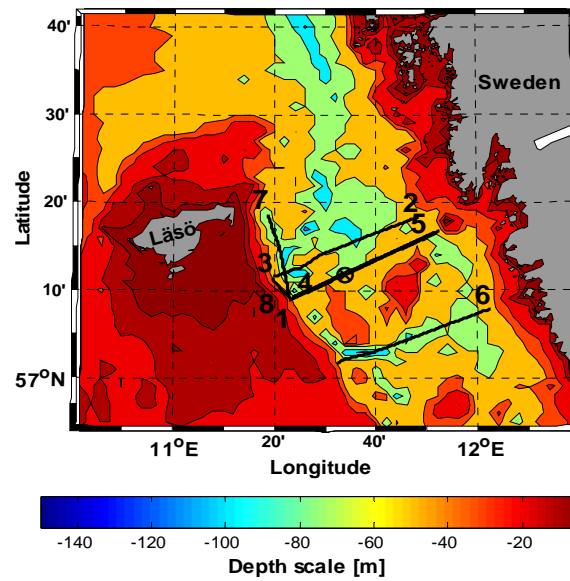
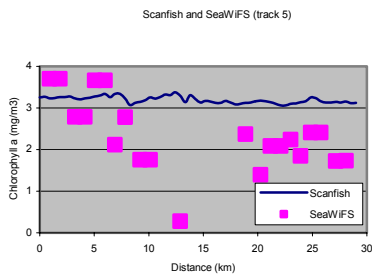
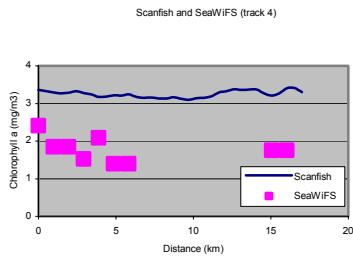
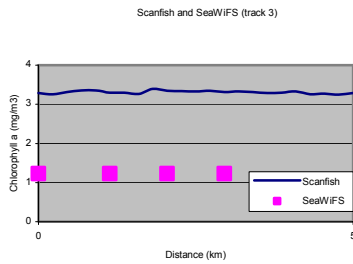
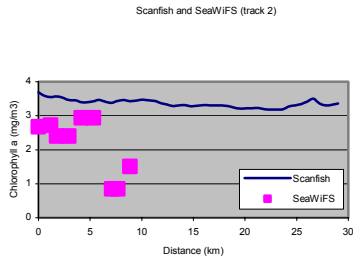


Figure 8-5 Shiptracks of ScanFish on the 6<sup>th</sup> to 10<sup>th</sup> August, 2001 in the Kattegat Sea. The buoy is moored at the position ` . The transect starts where the number is indicated, e.g. track2 (East to West), track 3 (North to South), track 4, (West to East) and track 5 (East to West).



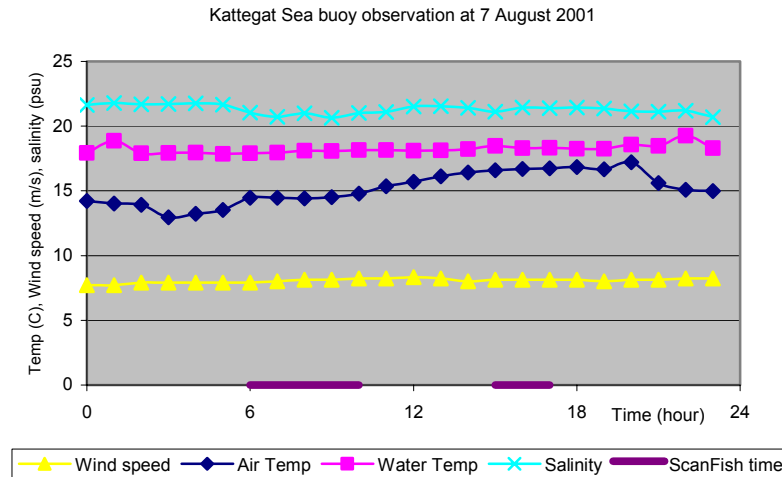
*Figure 8-6 ScanFish and SeaWiFS chlorophyll a observations in four horizontal transects in the Kattegat Sea from August 7th, 2001. Please refer to Figure 8-5 for the geo-position of the ship tracks.*

The first three transects show lower  $C_a$  values in the SeaWiFS scene than from ScanFish. The fourth transect shows in the first 8-km part,  $C_a$  values from SeaWiFS that varies between slightly higher and slightly lower values than from the ScanFish. However after 8 km of transect 4, SeaWiFS  $C_a$  values are lower than from the ScanFish. The first three ScanFish transects were collected from 6.04 to 10.13 a.m. whereas the last transect was collected from 15.13 to 17.25 p.m. local time. This means that the last transect is best collocated in time to the SeaWiFS scene (14.55 p.m.) as the ScanFish started sampling track 5 only 18 minutes after the SeaWiFS scene was recorded. The ship reach the 8 km



distance at around 37 minutes later, i.e. at 15.50 p.m. The buoy is geolocated in the ScanFish track 4 and 5 but unfortunately  $C_a$  was not successfully observed at the buoy.

The weather conditions as observed at the buoy shows very steady conditions, see Figure 8-7. The SeaWiFS resolution is gridded to 1000 m by 1000 m whereas the ScanFish observes at around half this length scale.



*Figure 8-7 Buoy observations of wind speed, air and sea temperatures and salinity at the time of the ScanFish transects from August 7<sup>th</sup>, 2001.*

In summary,  $C_a$  was observed from an experimental buoy equipped with a flourometer and from ScanFish flourometer observations in the Kattegat Sea during the summer of year 2001. Comparisons to the SeaWiFS satellite  $C_a$  maps reveals rather large deviations between the three types of observations. SeaWiFS and ScanFish seem to correspond well when almost truly collocated in space and time. Both sensors provide estimates of the spatial distribution of  $C_a$  and this is very important as the spatial variation is found to be large in the Kattegat Sea. The SeaWiFS and buoy observations are well collocated in time and space, however the large differences in  $C_a$  values between the two are unexplained at the moment.

With this limited data set a full evaluation of the reliability of satellite imagery as a coastal management and policy tool, for example, for forecasting and quantifying chlorophyll concentrations and the extent and severity of algal blooms is not fully met. An important learning though, is that the chlorophyll concentration is changing dramatically both in time and space in the Kattegat Sea.

Several algal blooms occurred in the Kattegat Sea prior to the SeaWiFS sensor, please refer to Chapter 10.

A suggestion for future measurements would be to plan the classical in-situ sampling co-located in time with the SeaWiFS and/or the new ENVISAT ocean colour sensor MERIS overpasses. In that way the optimum time-space mapping of the chlorophyll content would be achieved at approximately the same cost as is presently being used for this monitoring purpose.

## 9 Statistical correlation analysis of the marine biochemical data, hydrodynamic and atmospheric model results

In this section we have compared the atmospheric deposition and the estimated upward nitrogen fluxes with nitrogen loading from land. The objectives are:

1. To compare the different sources of external nitrogen to the euphotic zone on an annual and seasonal basis.
2. To identify temporal correlations between atmospheric deposition and entrainment events.
3. To identify any potential links between modeling results of atmospheric deposition and entrainment of nitrogen and marine observations of algae blooms.

It is anticipated that the land-based nitrogen loading will only affect the tributaries of Kattegat and potentially the coastal zone in the summer period, because the uptake of nitrogen is fast in the productive season where phytoplankton is nitrogen limited. Thus, for the analysis it is important to compare the atmospheric contribution with the upward mixing of nitrogen from below the pycnocline. The simultaneous dilution of phytoplankton biomass by entrainment of bottom water into the euphotic zone is negligible as the entrainment velocity is only a small fraction of the upper mixed layer.

### 9.1 Methods

The modeling results from the hydrographical and atmospheric deposition model were aggregated to yearly and seasonal values and compared with land-based nitrogen loading figures. The land-based nitrogen loading comprises the nitrogen load in freshwater discharges from Denmark and Sweden directly into Kattegat, except for the Göta River. Although the Göta River is a major source of nutrients, it discharges into the north-eastern part of Kattegat and the effect on Kattegat is marginal, because most of the discharges are diverted to Skagerrak.

Wind is one of the driving force for the hydrographical model and is therefore potentially correlated with the upward fluxes. Hence, the temporal correlations between atmospheric deposition, upward nitrogen fluxes for the three sub-basins and wind velocity were investigated by calculating the crosscorrelation function. Deposition rates, upward fluxes and wind velocities were log-transformed before the analysis to approximate normal distributions. The time series were prewhitened with an ARMA(1,1)-model (Box and Jenkins 1976) before the crosscorrelation analysis, because the time series are autocorrelated. If no prewhitening was carried out then the crosscorrelation function would be biased by the autocorrelation of the time series. The serial correlation in data was investigated by calculating the autocorrelation function (Box and Jenkins 1976).

Differences in flux rates delivered to the euphotic zone were analysed using t-test for log-transformed variables.

## 9.2 Results

The magnitude of the three external sources of nitrogen to Kattegat is shown in Figure 9.9-1. While the atmospheric deposition is rather stationary for both the inter-annual and seasonal variation, there are considerable variations in both the land-based load and upward flux of nitrogen. For the 11 year period considered, atmospheric deposition, upward flux of nitrogen and land-based load would account for 14%, 49% and 37%, respectively, of the total external loading to Kattegat. Thus, on an annual basis, the upward flux is the largest source of nitrogen. However, both the land-based nitrogen loading and the upward flux have strong seasonal variation caused by seasonal variations in freshwater runoff and winds, and these two sources of nitrogen are dominating during the winter period, where atmospheric deposition contributes less than 10% of the total nitrogen load to the euphotic zone. During the summer period (May-August), where the freshwater runoff is low and wind conditions are rather calm, atmospheric deposition of nitrogen becomes the dominating source of nitrogen, contributing approximately 40% of the external total nitrogen input to Kattegat.

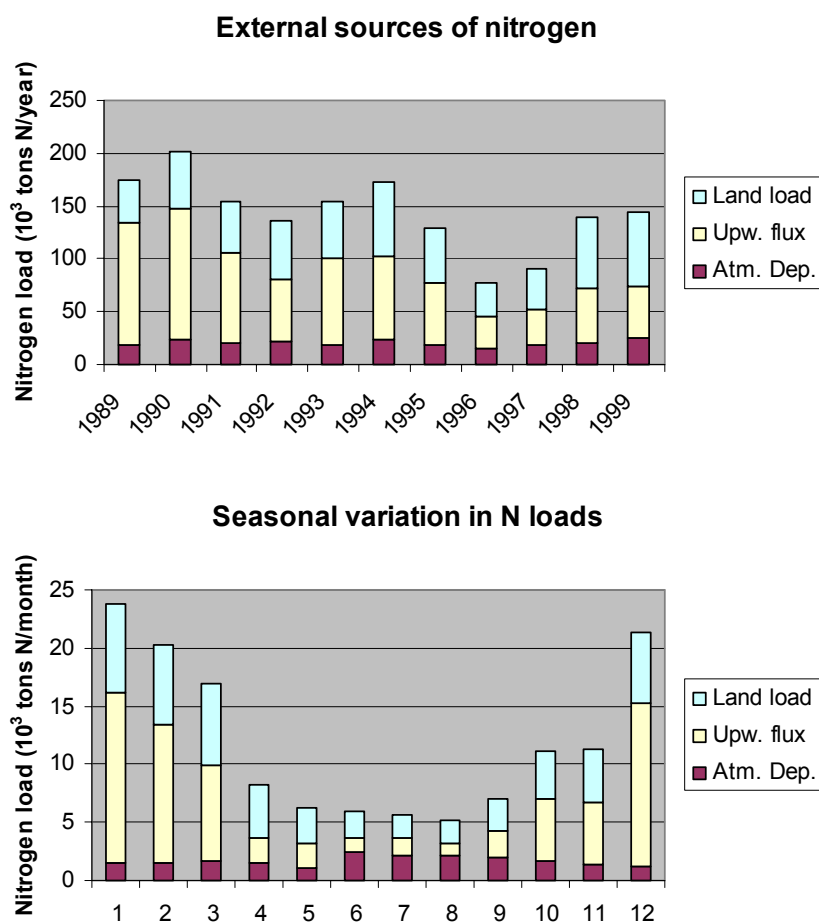


Figure 9.9-1. Interannual and seasonal variation in the external nitrogen sources to Kattegat.

The upward flux was calculated for three sub-basins in Kattegat and there were large differences between the fluxes in the 3 basins. While the nitrogen fluxes were of the same magnitude for the southern and central sub-basins, the northern sub-basin, where the Skagerrak-Kattegat front is located, gave upward fluxes that are 6 times larger than the other two sub-basins. This result has strong repercussions to the distribution between the different sources of external nitrogen. The overall ratio between atmospheric loading and upward fluxes were 0.11, 0.75 and 0.54 for the northern, central and southern sub-basins, respectively. For the summer period (May-August) this ratio was 0.52, 2.33 and 2.44 for the northern, central and southern sub-basin, respectively. Thus, the modeling approach shows that in the central and southern part of Kattegat, atmospheric deposition is the dominating source of external nitrogen. Based on the model calculations there are reasons to believe that summer algae blooms could potentially be caused by atmospheric deposition.

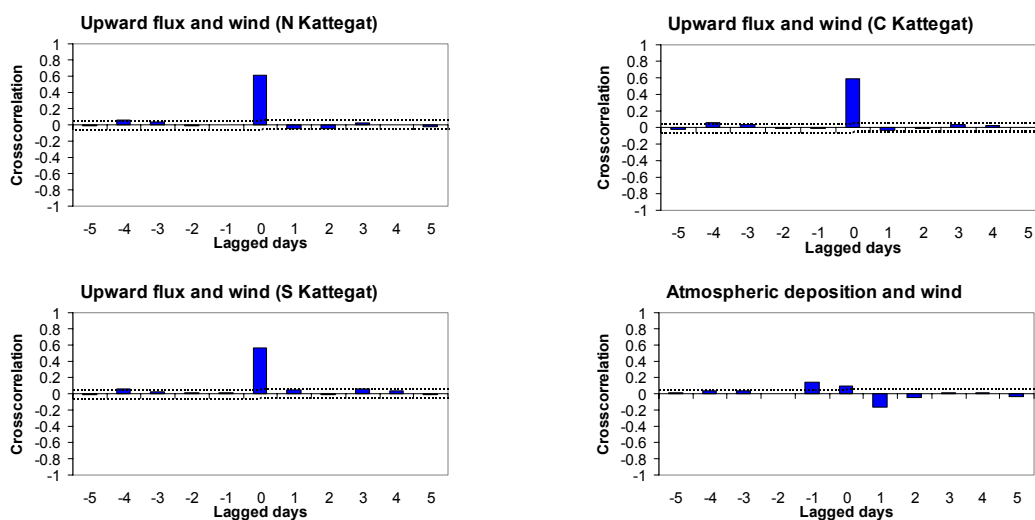


Figure 9.9-2. Upward fluxes of nitrogen and atmospheric deposition correlated in time to wind (all data log-transformed). Model output and wind measurements are aggregated to daily observations. Dotted lines are approximate 95% confidence limits for null hypothesis of no correlation. Data from May-August.

Figure 9.9-2 shows the crosscorrelation after prewhitening between model outputs and the major driving force for the hydrographical model, i.e. the wind velocity. The upward fluxes are significantly correlated (between 0.57 and 0.61) with the wind velocity on the same day. Thus, the response in the upward fluxes is rather fast – less than one day. The correlation between atmospheric deposition and wind is also significant for lags between –1 and 1 day although smaller than the wind to upward flux correlation. Atmospheric deposition appears to be positively related to the wind on the same day and the day before, but a negative significant correlation is observed for lag 1 day. This means that atmospheric deposition is negatively correlated to the wind velocity on the next day, which is in conflict with the general perception of causality. Disregarding this phenomenon the wind velocity appears to be partly driving both upward fluxes of nitrogen and atmospheric deposition. Investigating the crosscorrelation between atmospheric deposition and estimated upward fluxes of nitrogen also revealed significant correlations, however, of lesser magnitude. Thus, events of atmospheric deposition and upward fluxes appear to coincide.

Simultaneous events of atmospheric deposition and upward fluxes may not necessarily sustain a summer algae bloom. If we consider a realistic increase in chlorophyll *a* of 0.5 µg/l/day in the top 10 m water column, this would require an external supply of nitrogen of 44 mg N/m<sup>2</sup>/day based on the Redfield ratio and assuming a carbon to chlorophyll ratio of 50. The increase in chlorophyll *a* of 0.5 µg/l corresponds to an increase from the mean level that was used in the operational bloom definition in section 4. The external supply of nitrogen from entrainment and atmospheric deposition exceeded this threshold 51 days for the northern sub-basin, 9 days for the central sub-basin and 5 days for the southern sub-basin during the 11 year period from 1989-99 (~1353 observations for summer periods). These rates result in bloom frequencies much lower than described for the marine data analysis. This implies that the modeled nitrogen fluxes and atmospheric deposition on a single day cannot explain the amount of blooms in Kattegat.

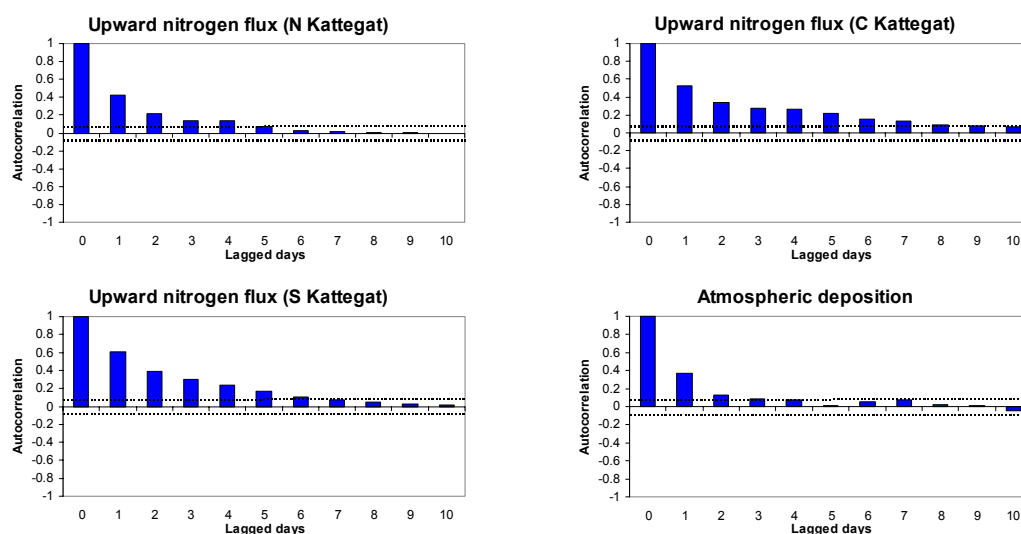


Figure 9.9-3. Autocorrelation of upward fluxes of nitrogen and atmospheric deposition (log-transformed). Dotted lines are approximate 95% confidence limits for null hypothesis of no autocorrelation. Data from May-August.

It is likely that several consecutive days of high external nitrogen input and not a single day alone caused the summer blooms. Thus, if we are to explain the observed summer algae blooms from the atmospheric and hydrographical model results, then it is unlikely that blooms are build-up over a single day and we should investigate the potential of building up a bloom over several days. In order to determine the number of days to use for aggregating data, we have calculated the autocorrelation function for the external nitrogen inputs Figure 9.9-3. While nitrogen fluxes from below the pycnocline typically have significant autocorrelations of 4-7 days, then the atmospheric deposition process changes slightly faster (significant autocorrelation up to 2 days lag).

Nutrient entrainment fluxes and atmospheric deposition time series were centered around their summer mean (May-August) to mimic the normal situation without any build-up of algae biomass. The accumulation of nitrogen inputs above the normal situation over 7 days was calculated. The accumulated external supply of nitrogen from entrainment and atmospheric deposition exceeded this threshold 165 days for the northern sub-basin, 69 days for the central sub-basin and 67 days for the southern sub-basin during the 11 year period from 1989-99 (~1353 observations for summer periods). These frequencies of blooms

correspond to the calculated bloom frequencies determined by marine observations.

Considering the aggregated supply of nitrogen to the euphotic zone there are many summer days over the 11 year period where the supply of nitrogen has the potential to build-up an increase in chlorophyll a above 0.5 µg/l. If we consider the days with a potential algae bloom build-up, we find that the dominating source of nitrogen supply is the upward flux (Table 9.9-1). For the southern and central sub-basins the upward nitrogen flux is approximately twice the atmospheric deposition rate. In the frontal zone (northern sub-basin) the upward nitrogen flux is more than 8 times the atmospheric deposition rate. Thus, although the atmospheric deposition is the dominating source of nitrogen in the summer period on the average, the periods with excess supply of nitrogen is dominated by fluxes from below the pycnocline. Hence, the entrainment process of nutrient from the lower layer into the euphotic zone is an episodic process, where periods with high winds enhances the mixing of nutrients over the pycnocline. This finding corresponds to the analyses carried out for marine data above.

*Table 9.9-1. Average daily entrainment and deposition fluxes for periods where there is a potential to build-up an algae bloom.*

Sub-basin	Upward nitrogen flux	Atmospheric deposition
Northern Kattegat	28.98 mg N/m <sup>2</sup> /day	3.49 mg N/m <sup>2</sup> /day
Central Kattegat	9.39 mg N/m <sup>2</sup> /day	5.31 mg N/m <sup>2</sup> /day
Southern Kattegat	10.55 mg N/m <sup>2</sup> /day	5.67 mg N/m <sup>2</sup> /day

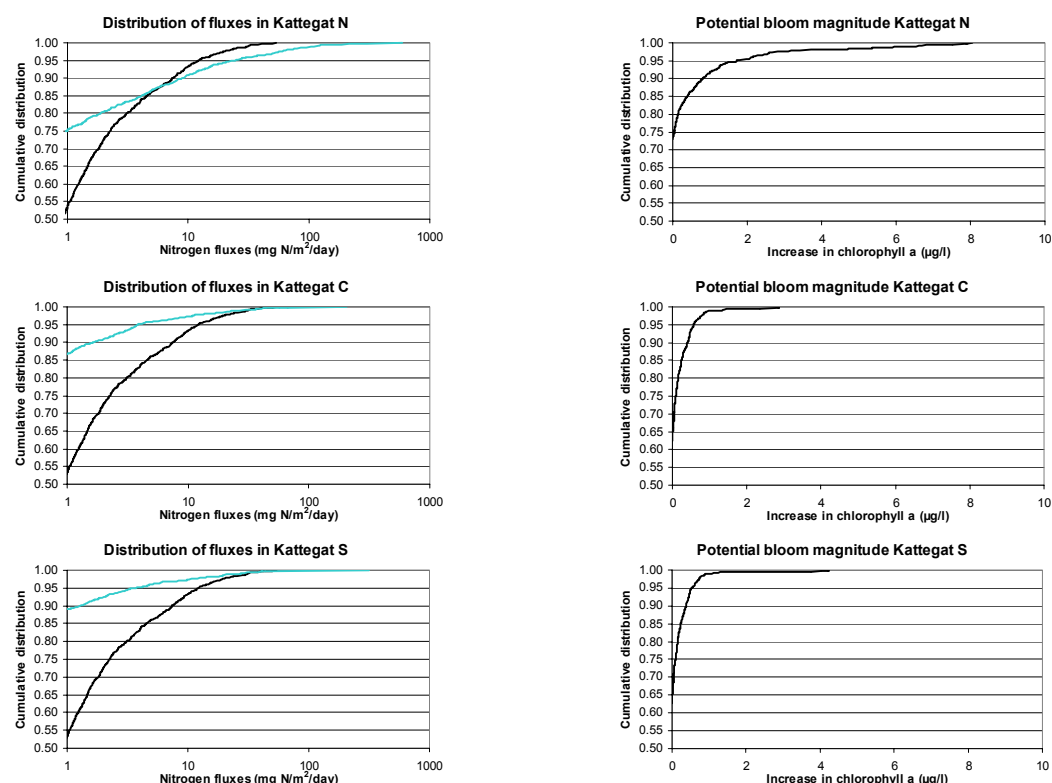


Figure 9.9-4. Left hand side: The cumulative distributions of daily atmospheric depositions (black lines) and upward fluxes (gray lines) in the 3 sub-basins. Right hand side: The accumulated supply of nitrogen to the 10 m euphotic zone converted into an increase in chlorophyll *a*. All distribution plots show the upper tail of the distribution (above the median).

The more episodic character of the upward fluxes is also observed in Figure 9.4 where the upward flux of nitrogen exceeds the atmospheric deposition for 12% of the days in the northern sub-basin and less than 1% of the days in the central and southern sub-basin. Combining this with the higher autocorrelation (Figure 9.9-3) of the upward fluxes then the accumulated upward flux over several days becomes more important.

The accumulated supply of nitrogen over 7 days (centered around the mean) is converted into a potential increase in chlorophyll *a* concentrations in Figure 9.4 (right hand plots). It is observed that the potential increase in chlorophyll *a* is larger in the northern sub-basin corresponding to the results obtained for the marine data analysis above. Typical increases in chlorophyll *a* are 2-8 µg/l for the northern sub-basin and 0.5-4.0 µg/l for the central and southern sub-basin.

The modeling results from the atmospheric deposition model and the hydrographical model were combined with the marine data from the monitoring programs in Denmark and Sweden. Table 9.9-2 shows that the fluxes to the euphotic zone from the atmosphere and below the pycnocline were in general higher on 5-8 days prior to sampling dates with blooms. The picture is not very clear due to two reasons:

1. The time between events of nitrogen supply to the euphotic zone and actual sampling may vary significantly and lagged values will include both days of low and high nitrogen loading.

2. Many stations are sampled on the same day, but the bloom definition does not always identify blooms at all stations on the same day. Due to the coarse spatial resolution of the two models, there will be nitrogen loading which at some stations corresponds to a bloom event and at other stations do not correspond to a bloom event.

It is very likely, that the significant differences that appear in Table 9.9-2 are simply driven by a few events with high nitrogen loading.

*Table 9.9-2. Differences in nitrogen supply rates for blooms versus non-blooms. P-values were determined from a t-test on log-transformed N fluxes. Significant differences are highlighted.*

Variable	Atmospheric dep.		Upward flux		Total N supply	
	$\Delta N$ (mg N/m <sup>2</sup> /d)	P value	$\Delta N$ (mg N/m <sup>2</sup> /d)	P value	$\Delta N$ (mg N/m <sup>2</sup> /d)	P value
Sampling day	0.0989	0.6900	-1.0906	0.2351	-0.9917	0.6243
Lag 1 day	0.0939	0.9602	-2.0041	0.1048	-1.9102	0.1901
Lag 2 days	-0.2927	0.0970	-0.1661	0.1039	-0.4588	0.5079
Lag 3 days	-0.1501	0.4810	0.0271	0.4530	-0.1230	0.5408
Lag 4 days	-0.5552	0.6616	1.0486	0.1450	0.4934	0.5138
Lag 5 days	0.4320	0.0402	4.9314	0.0009	5.3634	0.0002
Lag 6 days	-0.0595	0.2301	9.9604	0.0230	9.9009	0.0041
Lag 7 days	-0.3118	0.2604	1.8146	0.0139	1.5028	0.0352
Lag 8 days	1.0009	0.0107	2.6035	0.7491	3.6044	0.0226
Lag 9 days	0.3165	0.1404	0.9538	0.2482	1.2703	0.1823
Lag 10 days	-0.1436	0.2728	1.8131	0.0111	1.6695	0.0254
Lag 11 days	1.3694	0.0001	-0.7713	0.0097	0.5981	0.0008
Lag 12 days	0.6920	0.0294	-2.6166	0.3310	-1.9246	0.9289
Lag 13 days	0.0279	0.9722	-3.3327	0.0342	-3.3048	0.3854
Lag 14 days	0.5790	0.1152	0.8390	0.9345	1.4180	0.0192

If we look at the maximum flux supplied within the last 8 days prior to the sampling, we find that the upward flux and total flux were significantly higher for bloom situations versus non-bloom situations. There was no significant difference in the maximum atmospheric deposition rate. The same result applies to the mean flux supplied from atmosphere and below the pycnocline, ie significant difference between blooms and non-blooms situations for the upward and total fluxes.

Finally, it was investigated if there was a significant difference in the chlorophyll a measurements if the accumulated total nitrogen flux (centered around the mean) was above or below the threshold of 44 mg N/m<sup>2</sup>/day. The analysis was carried out on log-transformed observations taking local spatial variation into account by including the station as an effect. Although the chlorophyll a was approximately 20% higher if the total nitrogen flux exceeded the threshold, this result was not significant (P=0.1502).



## 9.3 Summary

Atmospheric deposition is on average the largest source of external nitrogen to the top 10 m water column in the summer period. However, the mixing of nutrient-rich water from below the pycnocline into the euphotic zone is a process of highly episodic character and provides sufficient nitrogen to the euphotic zone to sustain larger algae blooms. The two nitrogen loading processes are correlated – mainly because both are to some extent related to the wind velocity – and the nitrogen input from both processes enables the build-up of algae blooms. Furthermore, the nitrogen supplied on a single day cannot sustain a bloom with an increase above 0.5 µg/l chlorophyll a, but several consecutive days of high nitrogen inputs create the potential for blooms. In southern and central Kattegat the nitrogen input from below the pycnocline was approximately twice the atmospheric input, while northern Kattegat was completely dominated by upward mixing of nitrogen.

Significant relationships between bloom events and the nitrogen input processes were found – in particular, the relationship to upward mixing and total input was strong. The data do not, however, provide two distinct relationships that clearly separate both nitrogen input and chlorophyll a data into two groups. Using events of high nitrogen input as an indicator of blooms corresponded to a small increase in chlorophyll a concentration – although not significant.

# 10 Cases of algae bloom events in the Kattegat Sea

## 10.1 Algae bloom types, location and time

### 10.1.1 Statistical analysis

In order to identify bloom events an operational definition of a bloom was used

### 10.1.2 Bloom definition 1:

A bloom event is characterised by a phytoplankton biomass exceeding 200 µg/l or a chlorophyll a concentration exceeding 2.5 µg/l.

A total of 74 observations fulfilled this criterion for an algae bloom. The number of events may be considerably lower as some observations may belong to the same bloom event. Four events were identified, where measurements from more than one station indicated the presence of a bloom.

1. *15-17 August 1989.* Phytoplankton biomass concentrations were moderately high at station 409 and 413 (241 and 206 µg/l) although chlorophyll a concentration did not exceed the threshold of the bloom definition. The phytoplankton community was dominated by the diatom *Rhizosolenia Fragilisima* and the dinoflagellate *Ceratium tripos*.
2. *18-20 June 1990.* Phytoplankton biomass concentrations were high (735 µg/l) at station 190004 and dominated by the diatom *Rhizosolenia Fragilis-*

*sima*. High chlorophyll concentrations were observed at station 409 and 413 (3.7 and 2.7 µg/l, respectively).

3. *16-18 July 1990*. Phytoplankton biomass concentration was moderately high at station 409 (503 µg/l), but below 200 µg/l for stations 1001 and 190004. Chlorophyll a levels were high at 409 and 1001 (6.6 and 6.9 µg/l, respectively) and moderately high at station 190004 (2.8 µg/l). At station 409 the bloom was dominated by diatoms *Rhizosolenia Alata*, *Guinardia flaccida*, and the dinoflagellate *Ceratium tripos*. At station 1001 the bloom was dominated by the dinoflagellate *Gyrodinium aureolum*.
4. *15-18 July 1991*. Phytoplankton biomass concentrations were moderately high at station 409 and 413 (264 and 363 µg/l, respectively) although chlorophyll a concentration did not exceed the threshold of the bloom definition. The phytoplankton community was dominated by the diatoms *Rhizosolenia Fragilissima*, *Rhizosolenia Alata* and the dinoflagellates *Ceratium tripos*, *Peridinales*.

Analysing the spatial distribution of chlorophyll a and phytoplankton biomass revealed large differences between stations. The average chlorophyll, phytoplankton biomass concentrations, and primary production for Kattegat were looked at. Larger concentrations of phytoplankton biomass and chlorophyll are observed in the south-west part of Kattegat, while primary production appears to be more segregated into coastal stations and open sea stations – station 413 and 925 have lower values.

Studies have shown that the flux of nitrogen during an atmospheric deposition event is in the range 20-50 mg N/m<sup>2</sup>/d (Asman *et al.* 1995). Using the Redfield ratio for phytoplankton composition this corresponds to an additional primary production of 114-284 mg C/m<sup>2</sup>/d. Comparing this range to the average primary production found in Kattegat, it is found that an atmospheric deposition event could contribute approximately 50% of the average primary production.

Analyses of the frequency distribution for algae blooms is a currently ongoing process. The results hereof will be reported at a later stage.

## 10.2 Satellite observations, weather and sea surface temperatures

### 10.2.1 Satellite data analysis

There are four periods (Table 10.1) as defined in section 10.1 with observations of high chlorophyll in the Kattegat Sea. For these periods SST's have been retrieved from NASA Pathfinder archive. NOAA AVHRR quicklooks from Dundee are printed to overview the general weather conditions.

*Table 10.1. Time of four algal bloom events in the Kattegat Sea.*

Case number	Period
1	15-17 august 1989
2	18-20 june 1990
3	16-18 july 1990
4	15-18 july 1991

#### *15-17 August 1989*

The Kattegat Sea was covered by clouds through 14-16 August and was cloud free on the 17<sup>th</sup> as shown in the Dundee quicklooks. It is seen that the North Sea was cloud free and the Baltic Sea partly cloudy. The SST from the NASA Pathfinder data shows that the Kattegat Sea had a temperature gradient from north to south ranging from 14 °C near Skagen to 17 °C south of Anholt on the 17<sup>th</sup> aug 1989. When cloud covers the area, no information of SST is available.

#### *18-20 June 1990*

On the 18<sup>th</sup> June the southern part of the Kattegat Sea had temperatures ranging from 15 to 17 °C and from 15 to 16 °C in the western part on the 20<sup>th</sup> June. Clouds cover most of the Danish seas in this period.

#### *16-18 July 1990*

In this period the Kattegat Sea was partly cloudy. The SST was around 15 to 16 °C rising up to 17 °C in the western part of the sea on 18<sup>th</sup> July. From the Dundee quicklooks it is clear that there was a long sunny spell in the days prior. The sunny weather started on July 12<sup>th</sup> 1991.

#### *15-18 July 1991*

The Kattegat Sea was partly cloudy and SST was 15 °C in the northern part and 17 °C in the southern part. Denmark, the North Sea and the Baltic Sea was heavily clouded through the period (Dundee quicklooks are not shown, it's all clouds).

## **10.3 Summary**

Data from 10 years have been analysed to identify algae bloom events that could be caused by atmospheric deposition of nitrogen. Four events have been selected and studied in detail. The phytoplankton composition for the four events was dominated by diatoms, secondarily by dinoflagellates.

The spatial distribution of chlorophyll and phytoplankton biomass show the highest concentrations in the south-western part of Kattegat. Atmospheric deposition rates converted into phytoplankton production have been shown to be relatively small compared to average primary production measurements.

NOAA AVHRR data from the NASA Pathfinder archive show the daily SST at a 9 km \* 9 km grid for the four periods. Only on 17 Aug 1989 is Kattegat cloud

free. Several other days are partly cloud free: 18 June 1990, 16 & 18 July 1990 and 17 & 18 July 1991. The rest of the days are cloud covered.

From the NOAA AVHRR quicklooks archive in Dundee, the same general observations are made. The Dundee data may be bought and processed in a 1 km \* 1 km resolution.

Archives on sea winds are available since August 1991, i.e. later than the four periods of high biological activity in the last decade. SSM/I has a too poor resolution (footprint) for the Kattegat Sea to be mapped.

Looking at the monthly mean SST of February and August (Roozekrans, 1999) it shows the warmest conditions in Feb. 1990 for Kattegat but a normal Aug. 1990. Later in the decade very much warmer winter and summer conditions have appeared, e.g. Aug. 1994, 1995 and 1997.

## 11 Conclusion

The retrospective analysis investigates links between atmospheric nitrogen deposition and algal bloom development. The analysis covers the Kattegat Sea in the summer periods from April to September during the years 1989-1999.

The retrospective analysis is based on atmospheric deposition model results, hydrodynamic deep-water flux results, phytoplankton abundance observations from Danish and Swedish monitoring stations and optical satellite data. A data matrix of atmospheric and oceanographic nutrient fluxes and algal blooms, containing meteorological, air chemistry, and water chemistry measurements are collected and are available at

<http://www.dmu.dk/AtmosphericEnvironment/MEAD>.

The deposition of nitrogen to the Kattegat area has been calculated with the atmospheric transport-chemistry model ACDEP. The resolution of the data is 30 km \* 30 km. All inorganic components relevant for atmospheric deposition are included in the model. Approximately 70 % of the deposition consists of wet deposition of highly episodic nature.

A basin-scale hydrodynamic model has been used to estimate the flux of nutrients to the mixed layer by wind forced entrainment. The hydrodynamic model resolves the Kattegat horizontally with three sub-basins and in the vertical with 50 layers. The mixed layer dynamics is parameterized with a bulk approach. The focus is to estimate the magnitude and frequency of mixing events that can feed the mixed layer with nutrients from below. The methodology is to use observed salinity-nutrient relations with monthly resolution together with the modeled entrainment rate to estimate the nutrient flux. The nutrient fluxes are calculated in a way that probably will not give the total upwelling of nutrients in Kattegat, but the resulting time-series represent an order of magnitude estimate of the entrainment fluxes and their frequency.

The results from the atmospheric and hydrodynamic models are presented as time series of total atmospheric nitrogen deposition, atmospheric wet deposition together with nitrogen fluxes from the bottom waters to the surface layer. At-

atmospheric deposition rates converted into phytoplankton production are relatively small compared to average primary production measurements. The atmospheric deposition of nitrogen is of the same order of magnitude as the flux from the bottom waters. Yet the cumulative atmospheric deposition is always larger than the marine deep-water flux.

Atmospheric deposition is on average the largest source of external nitrogen to the top 10 m water column in the summer period. However, the mixing of nutrient-rich water from below the pycnocline into the euphotic zone is a process of highly episodic character and provides sufficient nitrogen to the euphotic zone to sustain larger algae blooms. The two nitrogen loading processes are correlated – mainly because both are to some extent related to the wind velocity – and the nitrogen input from both processes enables the build-up of algae blooms. Furthermore, the nitrogen supplied on a single day cannot sustain a bloom with an increase above 0.5 µg/l chlorophyll a, but several consecutive days of high nitrogen inputs create the potential for blooms. In southern and central Kattegat the nitrogen input from below the pycnocline was approximately twice the atmospheric input, while northern Kattegat was completely dominated by upward mixing of nitrogen.

Significant relationships between bloom events and the nitrogen input processes were found – in particular, the relationship to upward mixing and total input was strong. The data do not, however, provide two distinct relationships that clearly separate both nitrogen input and chlorophyll a data into two groups. Using events of high nitrogen input as an indicator of blooms corresponded to a small increase in chlorophyll a concentration – although not significant.

The distributions of chlorophyll a in terms of both mean and extreme values have large spatial variations that need to be taken into account. The areas in Kattegat where high chlorophyll a concentrations are measured are close to major freshwater sources with high nutrient loading or in the frontal zone in the northern part, where Kattegat water mixes with high saline water from Skagerrak. The central southern part has the lowest concentrations and this area is dominated by Baltic Sea water. The spatial distributions of chlorophyll and phytoplankton biomass show the highest concentrations in the south-western part of Kattegat.

The spatial distribution of frequency of blooms results in a different picture. Areas that are hydrographically active with high turbulent mixing have the highest frequency of blooms. These areas are the frontal zone in Northern Kattegat, the outflow areas in Southern Kattegat where Baltic Sea water is diverted through the Great Belt or the Sound.

The physical and chemical conditions before and during a bloom revealed that blooms occurred under higher salinity and wind conditions on 2-6 days prior to the observed bloom. Significant increases in DIN and DSi were also observed at a number of stations. This clearly indicates that the major cause of blooms occurring in Kattegat is due to mixing of nutrient-rich bottom water into the euphotic zone.

Finally, the blooms were dominated by diatoms and dinoflagellates species – mainly *Rhizosolenia* spp. and *Ceratium* spp. *Ceratium* is a species, which typically is observed around the pycnocline, but it can be mixed up into the euphotic zone and remain in the surface layer provided that nutrient conditions are favorable. The characteristics of the other species are less pronounced and do

not give any clear indications of the causes of the blooms. Thus, the phytoplankton composition also indicates that blooms are most likely due to wind-forced mixing of nutrient-rich bottom water into the surface layer.

Data from 10 years have been analysed to identify algae bloom events that could be caused by atmospheric deposition of nitrogen. Four algal bloom events were identified. The phytoplankton composition was dominated by diatoms, secondarily by dinoflagellates during these events.

The analysis of SeaWiFS satellite chlorophyll maps shows very large local gradients in the Kattegat Sea. The comparison to the ScanFish shows good agreement when the data sets are well collocated in space and time. The time is apparently very important in the Kattegat Sea as also evidenced by the buoy observations on chlorophyll. Surprisingly, the buoy data and SeaWiFS are not showing the same chlorophyll values, even though the two data sets are collocated. The calibration of the buoy data is still under investigation.

The exploitation plan in the MEAD project is to set-up realistic scenario model runs based on the statistical knowledge on cause-effect relations between atmospheric and marine nitrogen fluxes to the surface waters in the Kattegat Sea. The results of the retrospective analysis offer insight into the order of magnitude of dry and wet deposition as well as deep-water flux of nutrients to the marine surface layer. So through this in-depth analysis it is possible to select representative and realistic scenarios for the modeling of the atmospheric and marine extreme events that are likely to cause algal blooms.

#### **11.1.1 Acknowledgements**

Funding from EC for the project Marine Effects of Atmospheric Deposition project (MEAD) (<http://www.uea.ac.uk/env/mead/>), contract EVK3-CT-1999-00014 is acknowledged. Furthermore the project S-MEAD granting access to the SeaWiFS satellite scenes from NASA, retrieved from the Dundee station, and GRAS A/S at which Lotte Nyborg and Michael Schultz Rasmussen has contributed by processing of the SeaWiFS scenes is greatly appreciated. Atmospheric observations and model results from Anholt and the ACDEP model (NERI/ATMI), in-situ chlorophyll (NERI/HAMI and SMHI), hydrodynamical model results and ScanFish data (Gothenburg University) and buoy data (SMHI) are acknowledged.

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# Appendix A List of publications

## Peer reviewed articles:

Hasager, C.B., J. Carstensen, B. Gustafson, O. Hertel, M. Johnsson, S. Markager and C. Skjødth, 2003 On extreme atmospheric and marine nitrogen fluxes and chlorophyll-a levels in the Kattegat Sea. *Atmospheric Chemistry and Physics* (submitted)

Carstensen, J., Conley, D. and Henriksen, P. 2003 Summer algal blooms in a shallow coastal ecosystem, the Kattegat. 1. Frequency and composition of phytoplankton blooms (in. prep.)

Carstensen, J., Frohn, L.M., Hasager, C.B., Gustafsson, B. 2003 Summer algal blooms in a shallow coastal ecosystem, the Kattegat. 2. Quantification and comparison of nitrogen fluxes. (in prep.)

## Non refereed literature:

Carstensen, J., D.J. Conley, P. Henriksen (2003) Frequency and composition of algal blooms in a shallow coastal ecosystem, the Kattegat. In preparation for *Limnology and Oceanography*.

Carstensen, J., L.M. Frohn, C.B. Hasager, B. Gustafsson (2003) Summer algal blooms in a shallow coastal ecosystem, the Kattegat: Quantification and comparison of nitrogen fluxes. In preparation for *Estuarine, Coastal and Shelf Science*.

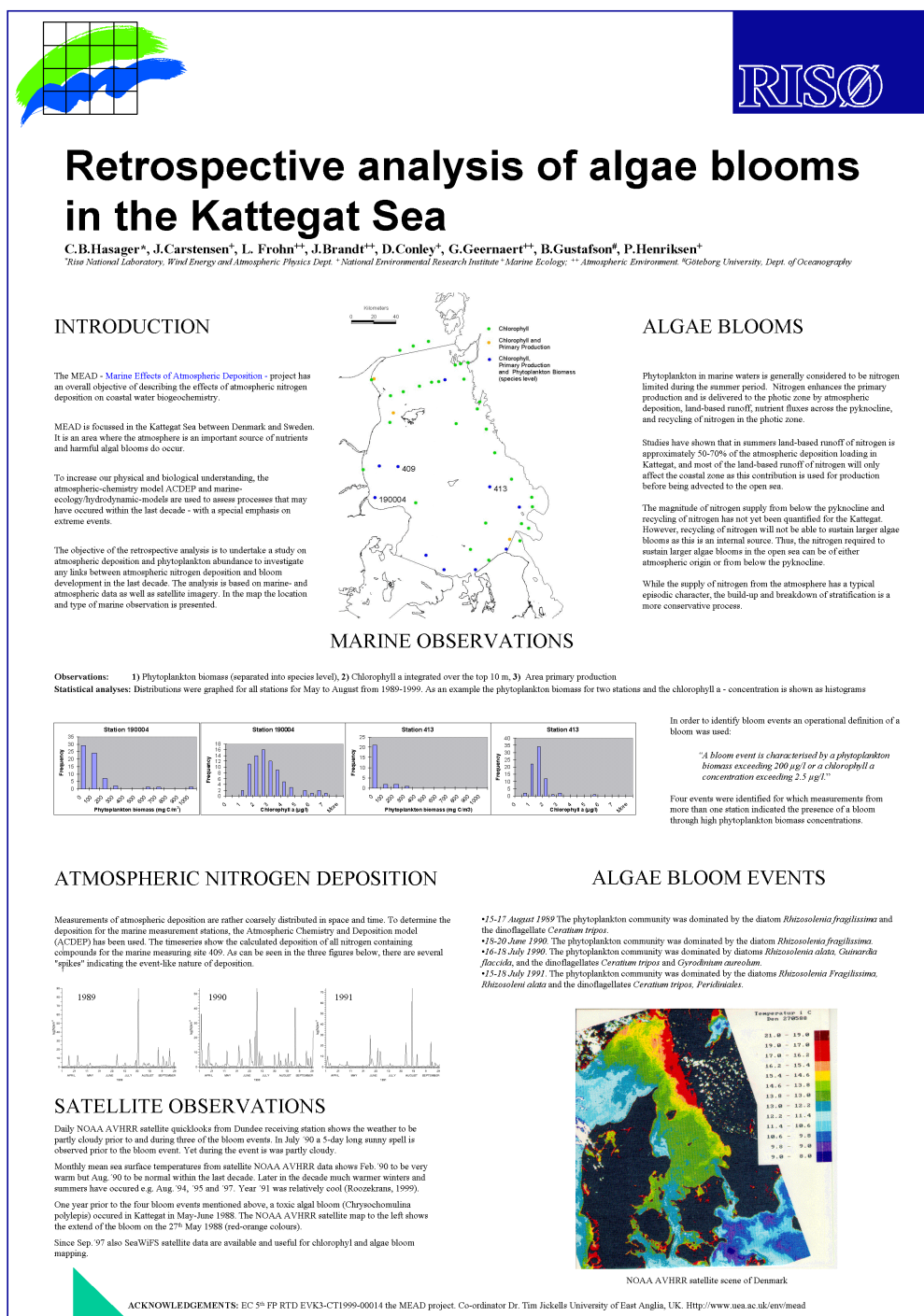
Hasager, C.B., Carstensen, J., Frohn, L.M., Brandt, J., Conley, D., Geernaert, G., Gustafson, B., Henriksen, P. 2000 Retrospective analysis of algae blooms in the Kattegat Sea, *DSAR annual meeting, 9.11.2000*, Eigtveds Pakhus, Copenhagen [Download Poster \(1.25 MB pdf\)](#)  
find the link at <http://www.risoe.dk/vea-atu/atmocean/mead.htm>

Hasager, C.B., Carstensen, J., Frohn, L. M, Brandt, J., Conley, D., Geernaert, G., Gustafson, B., Henriksen, P. and O.Hertel (2001) Retrospective analysis of marine effects of atmospheric nitrogen deposition in the Kattegat Sea. March in *EGS XXVI General Assembly, Nice, France, 25-30 March 2001 [OA14.03] Surface fluxes over land and ocean: Physics of sea-air, land-air and ice-air fluxes* <http://www.copernicus.org/EGS/egsga/nice01/programme/abstracts/aai2216.pdf>

Hasager et al. 2003 On extreme nitrogen events and chlorophyll a in the Kattegat Sea, *EGS-AGU-EUG General Assembly, 6-11 April 2003, Nice, France, Session BG1.16 Atmospheric and oceanic processes in air-sea exchange: first results from SOLAS studies* (in prep.)

Sørensen, L.L., Hasager, C.B., Pryor, S. and Sempreviva, A.M., 2001. Marine Effects from Atmospheric Deposition (MEAD) *DSAR annual meeting, 15.11.2001*, Eigtveds Pakhus, Copenhagen, see [poster \(811 kB pdf\)](#)

# Appendix B Hasager *et al.* DSAR 2000



Hasager, C.B., Carstensen, J., Frohn, L.M., Brandt, J., Conley, D., Geernaert, G., Gustafson, B., Henriksen, P. 2000 Retrospective analysis of algae blooms in the Kattegat Sea, *DSAR annual meeting, 9.11.2000*, Eigtveds Pakhus, Copenhagen.

# Appendix C Hasager *et al.* EGS 2001

Abstract at oral presentation at

EGS (European Geophysical Society) XXVI General Assembly, Nice, France, 25-30 March 2001 Session OA14.03 Surface fluxes over land and ocean: Physics of sea-air, land-air and ice-air fluxes

## RETROSPECTIVE ANALYSIS OF MARINE EFFECTS OF ATMOSPHERIC NITROGEN DEPOSITION IN THE KATTEGAT SEA

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The hypothesis of the study is that atmospheric nitrogen deposition may trigger harmful algae blooms. Studies show that in summers the land-based runoff of nitrogen is approximately 50-70 % of the atmospheric deposition loading in the Kattegat Sea located at 57°N, 12°E between Denmark and Sweden. The supply of nitrogen from the atmosphere to the sea surface has a typical episodic character. In the study the nitrogen deposition is calculated by the ACDEP (Atmospheric Chemistry and Deposition model). The network of atmospheric deposition data is scarce and the ACDEP model results cover both the spatial and temporal scales of interest. Marine observations of phytoplankton (separated into species level), chlorophyll *a* integrated over the top 10 m and area primary production is analysed statistically. Based on this analysis statistically-based definitions of extreme marine events are defined. Several algae bloom events are found in this way and the associated history of weather, physiographic marine characteristics and optical satellite remote sensing observations are included in the analysis. The retrospective analysis covers the period May to August 1989 to 1999 based on the Danish and Swedish data. The study is part of the EU project MEAD (Marine Effects of Atmospheric Deposition). Funding from EVK3-CT1999-00014 is acknowledged.

# Appendix D Carstensen *et al.* ASLO 2001

**Abstract at oral presentation at ASLO (American Society of Limnology and Oceanography), Aquatic Sciences**

**Conference in Albuquerque New Mexico, USA feb 2001**

## FREQUENCY ANALYSIS OF ALGAE BLOOMS IN KATTEGAT

Carstensen, J., S. Markager, P. Henriksen

### Abstract:

Algae blooms occur frequently during the summer period in Kattegat, an estuarine area which limits the Baltic Sea to the North Sea. Recent estimates suggest that about 60 % of the nitrogen loading comes from the atmosphere during the summer period and the overall goal was to link algae blooms with nutrient input events using frequency analysis techniques. Measurements of chlorophyll, primary production and phytoplankton biomass from the Swedish and Danish national monitoring programs (1989-99) have been analyzed to determine values with a 10-year return period, i.e. the values that statistically will be exceeded once every 10 years. The analysis has revealed large spatial variations where the shallow western part of Kattegat is more frequently exposed to algae bloom of greater magnitude than the deeper eastern part. In addition, summer algae blooms were often dominated by single opportunistic species. The analysis can be applied to longer time periods to detect changes in frequency and magnitude of algae blooms.

# Appendix E Carstensen *et al.* ERF 2001

**16th Biennial Conference of the Estuarine Research Federation.  
ERF2001: An Estuarine Odyssey. 4-8. November 2001. St. Pete  
Beach, Florida.**

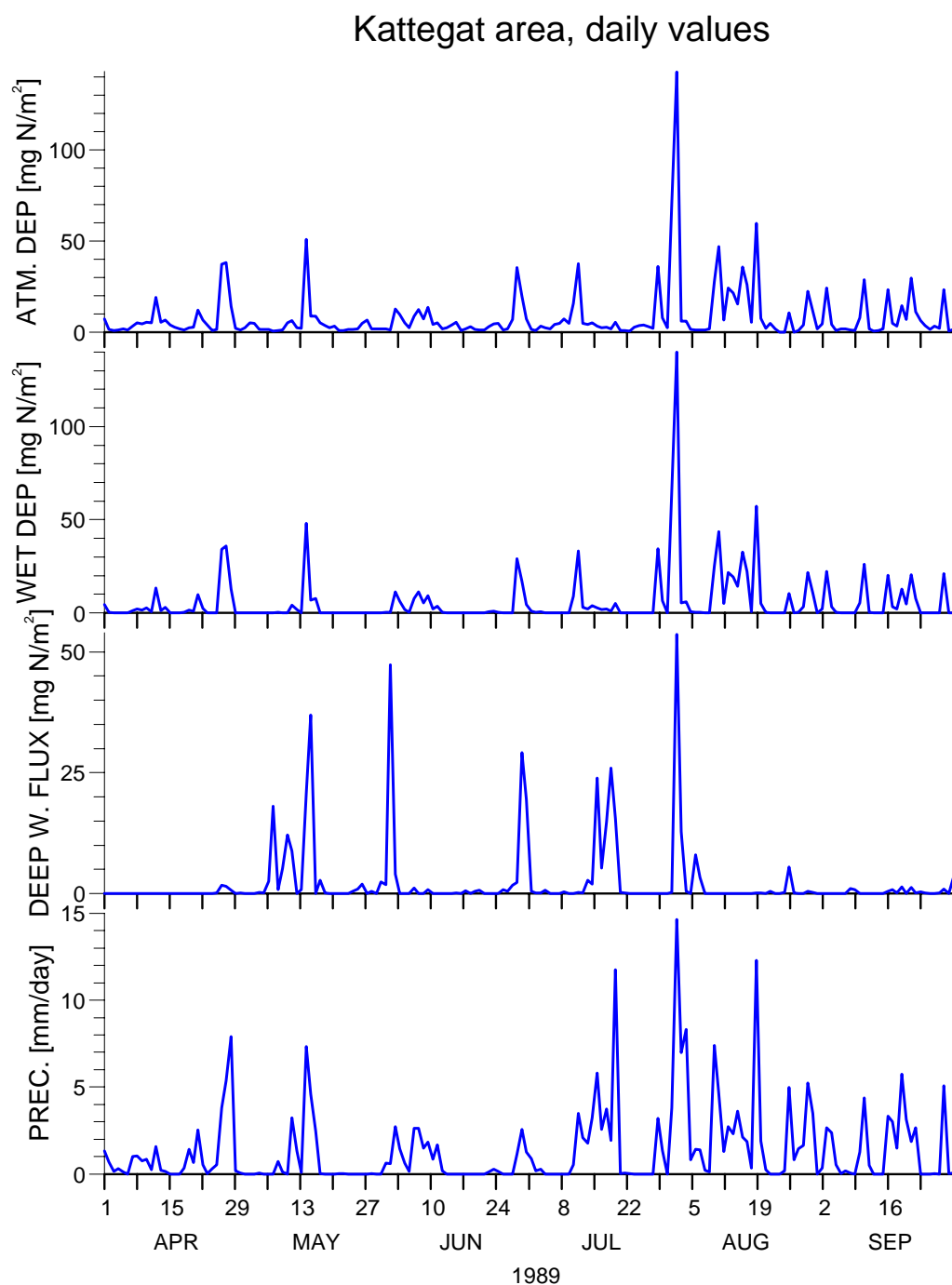
Abstract:

## EFFECT OF ATMOSPHERIC DEPOSITION OF NITROGEN ON SUMMER ALGAL BLOOMS IN KATTEGAT

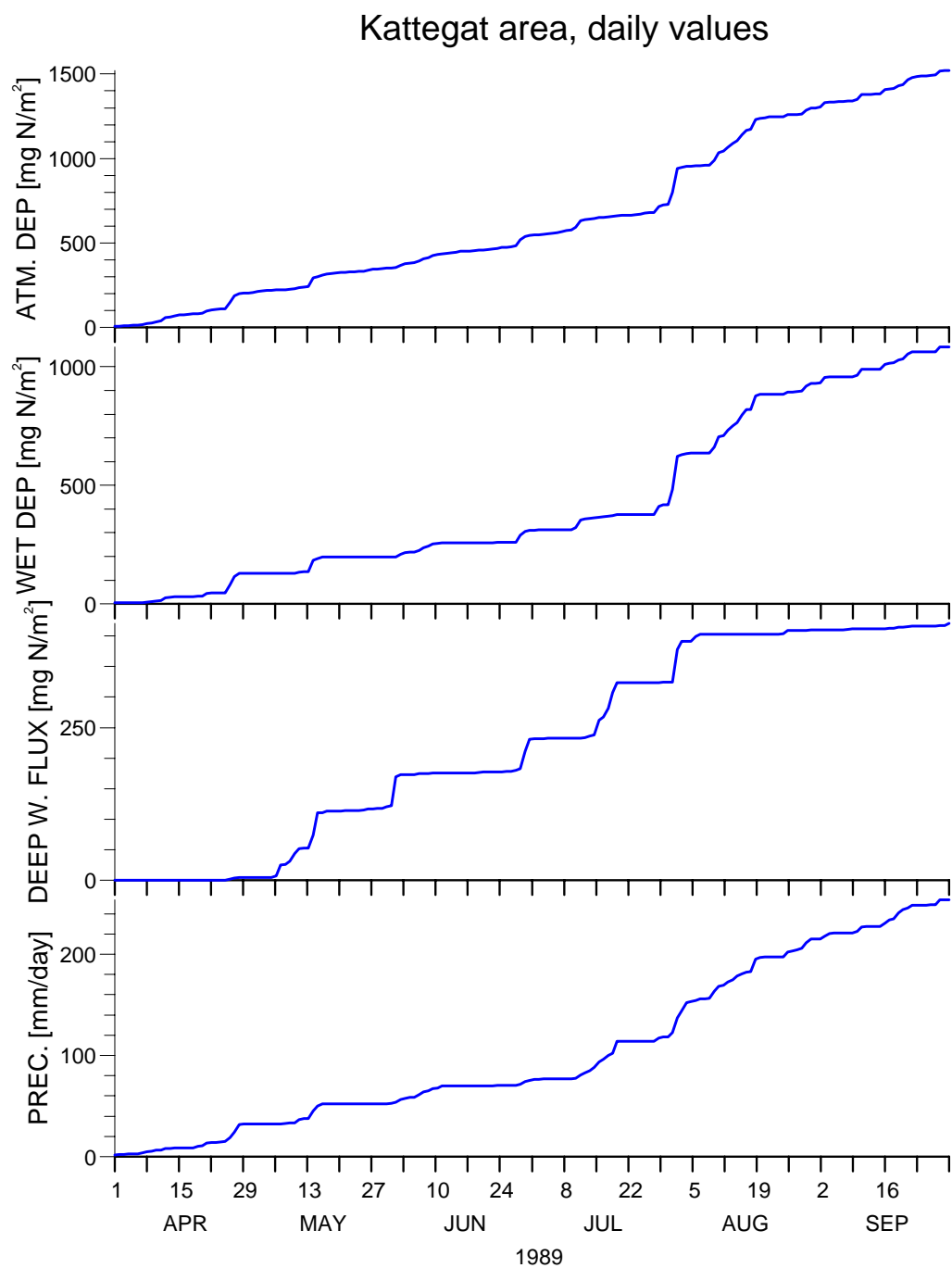
J. Carstensen, L.M. Frohn and B. Gustafsson

The external loading of nitrogen to the Kattegat is dominated by atmospheric deposition in the summer period (May-August). It is hypothesized that this source of new nitrogen could be the cause of frequent reoccurring summer algal blooms. We have made a statistical analysis of chlorophyll measurements from the national monitoring programs in Denmark and Sweden (1989-99) to identify events of summer blooms and link these to physical variables. Large spatial variations in frequency and magnitude of blooms were observed. Three specific areas within Kattegat, dominated by entrainment processes, were identified as having relatively higher frequencies of algal blooms. Variations in salinity and wind velocity further confirms that nitrogen supplied from below the pycnocline was the most likely cause of summer algal blooms. Models for describing the atmospheric deposition of nitrogen and the transport of nutrients over the pycnocline have been developed and results compared. This modeling study has shown that entrainment was the dominating source of new nitrogen to the euphotic zone. Summer algal blooms could be sustained by atmospheric deposition events, but these were less frequent than blooms sustained by entrainment.

## Appendix F

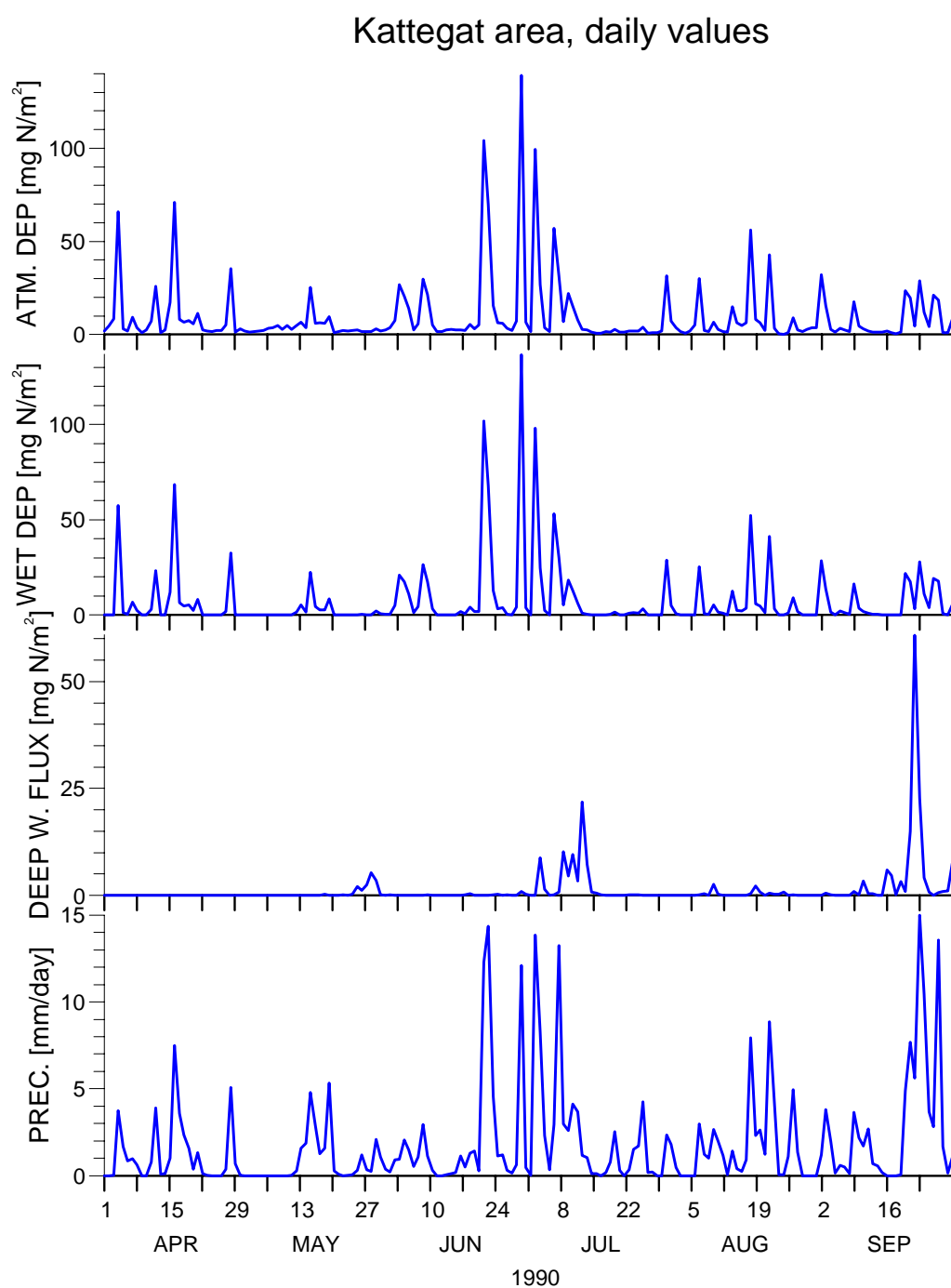


*Figure I. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1989.*

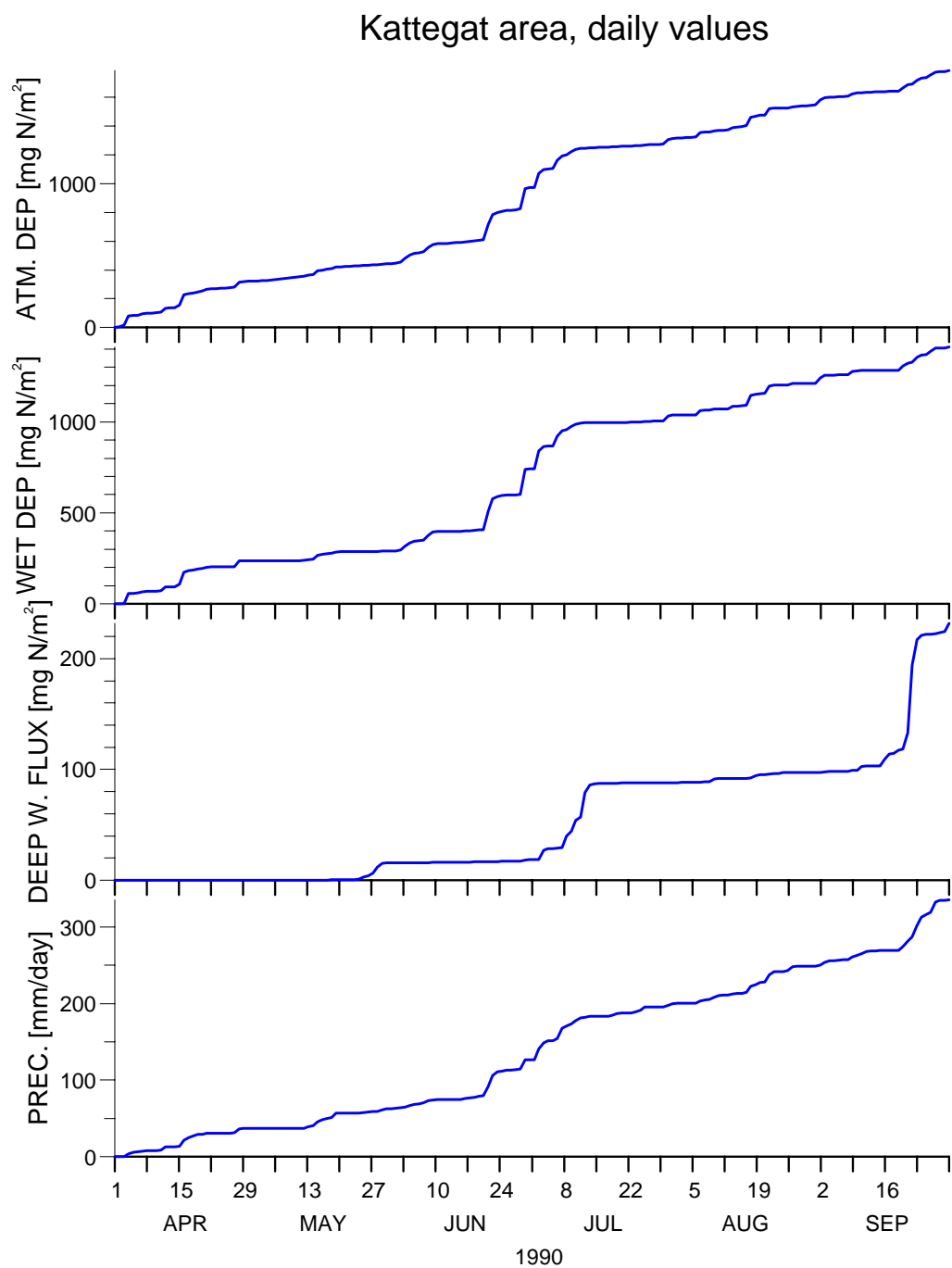


*Figure II. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1989.*

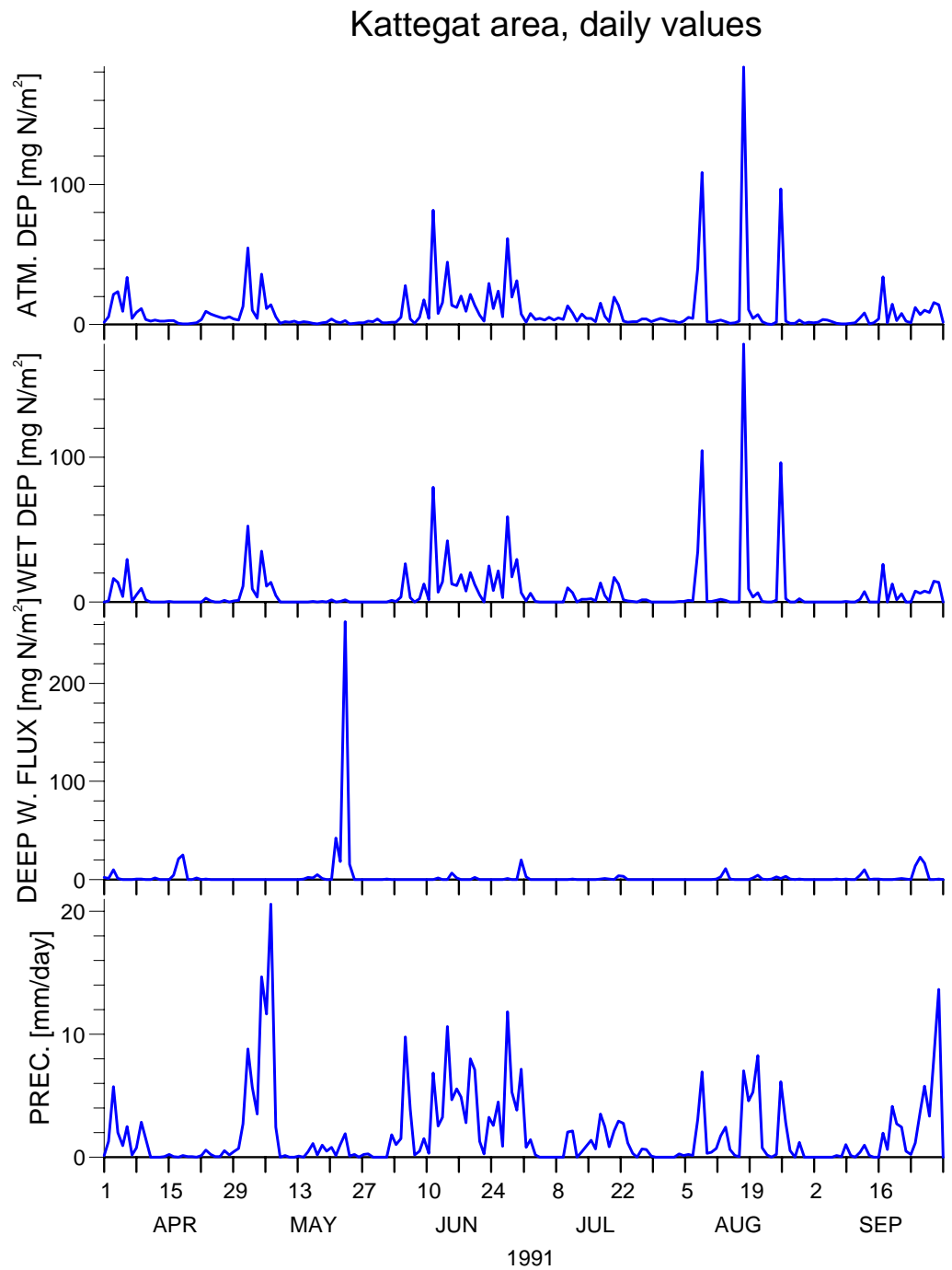




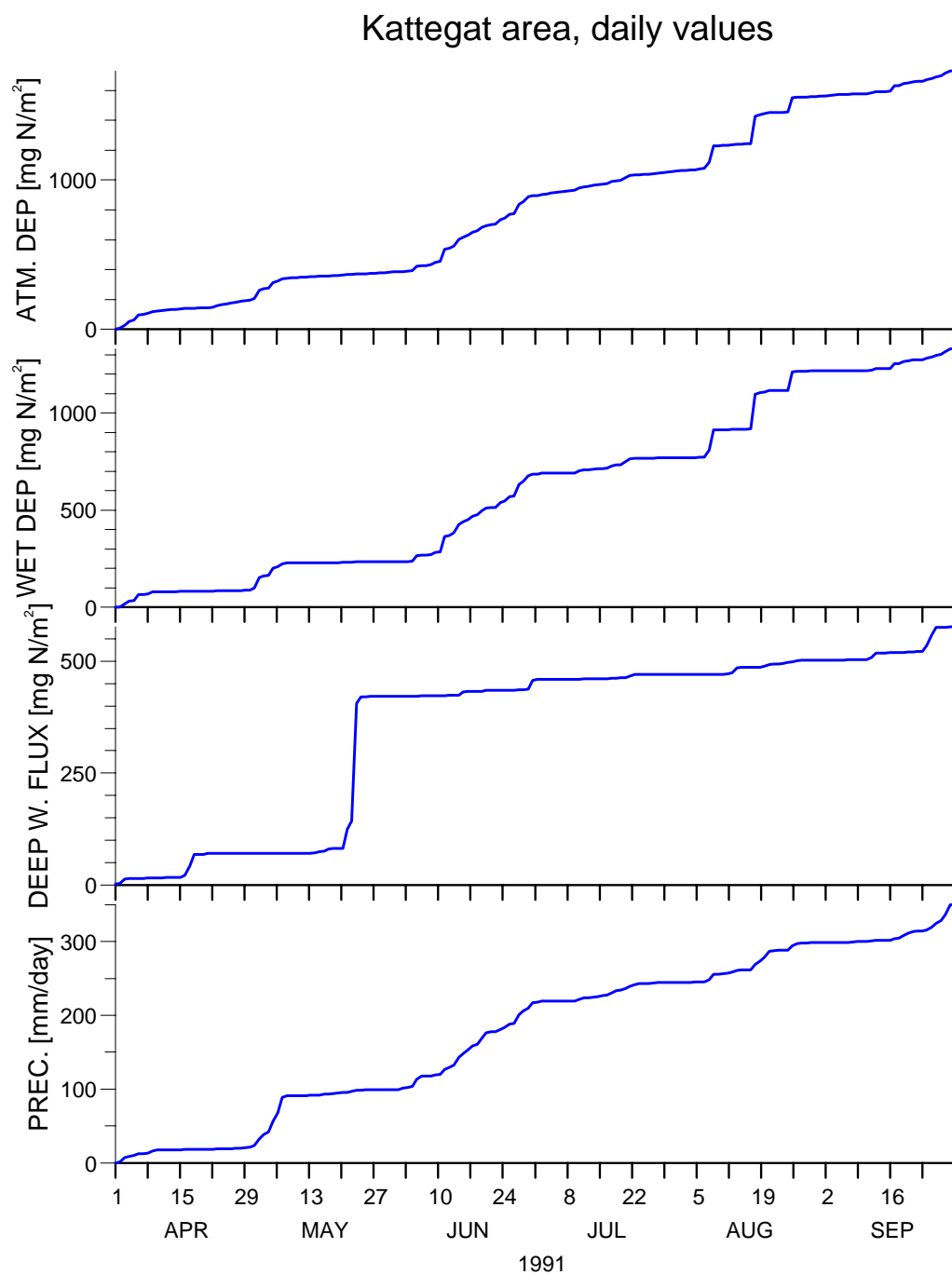
*Figure III . Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1990.*



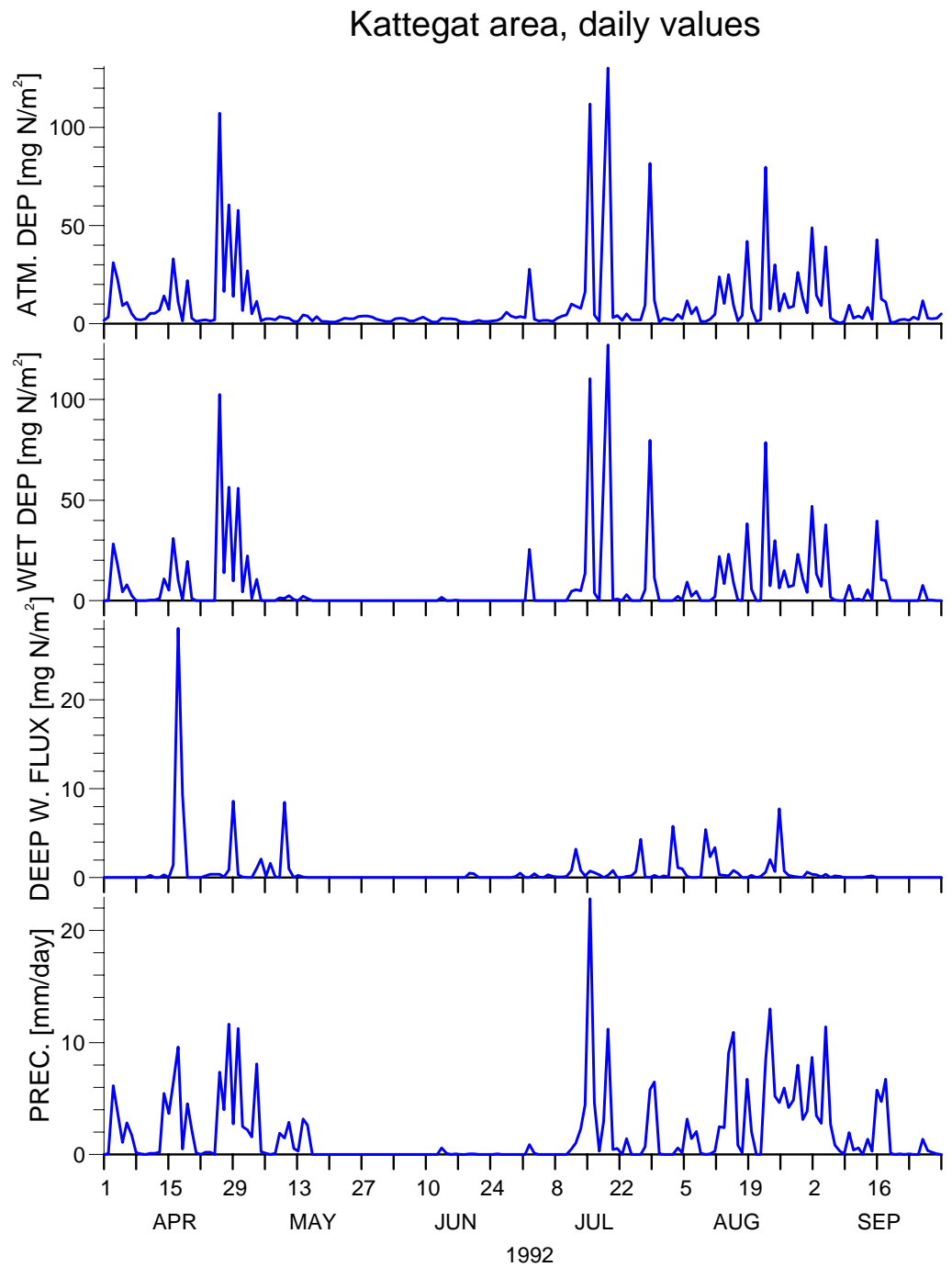
*Figure IV. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1990.*



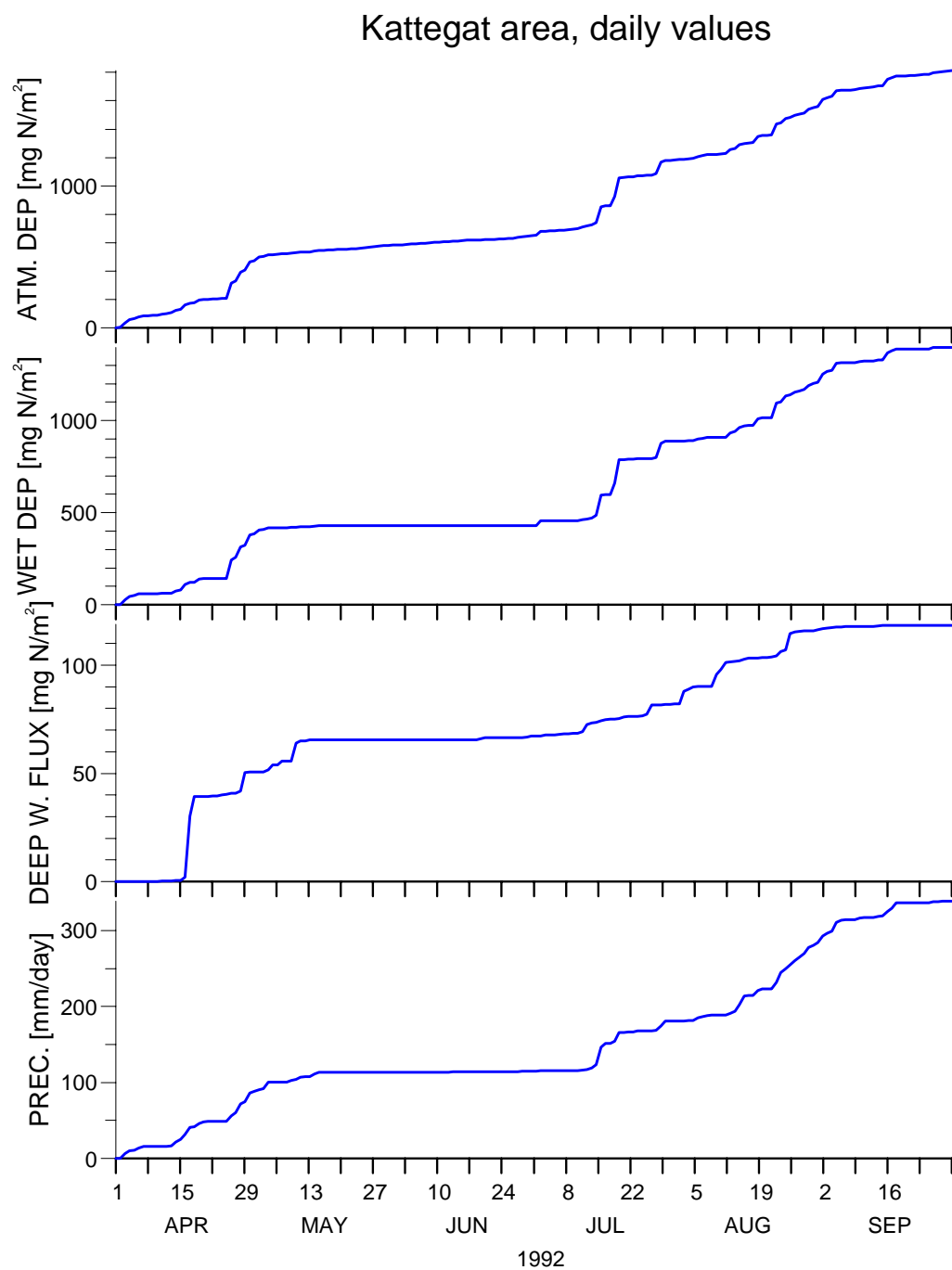
*Figure V. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1991.*



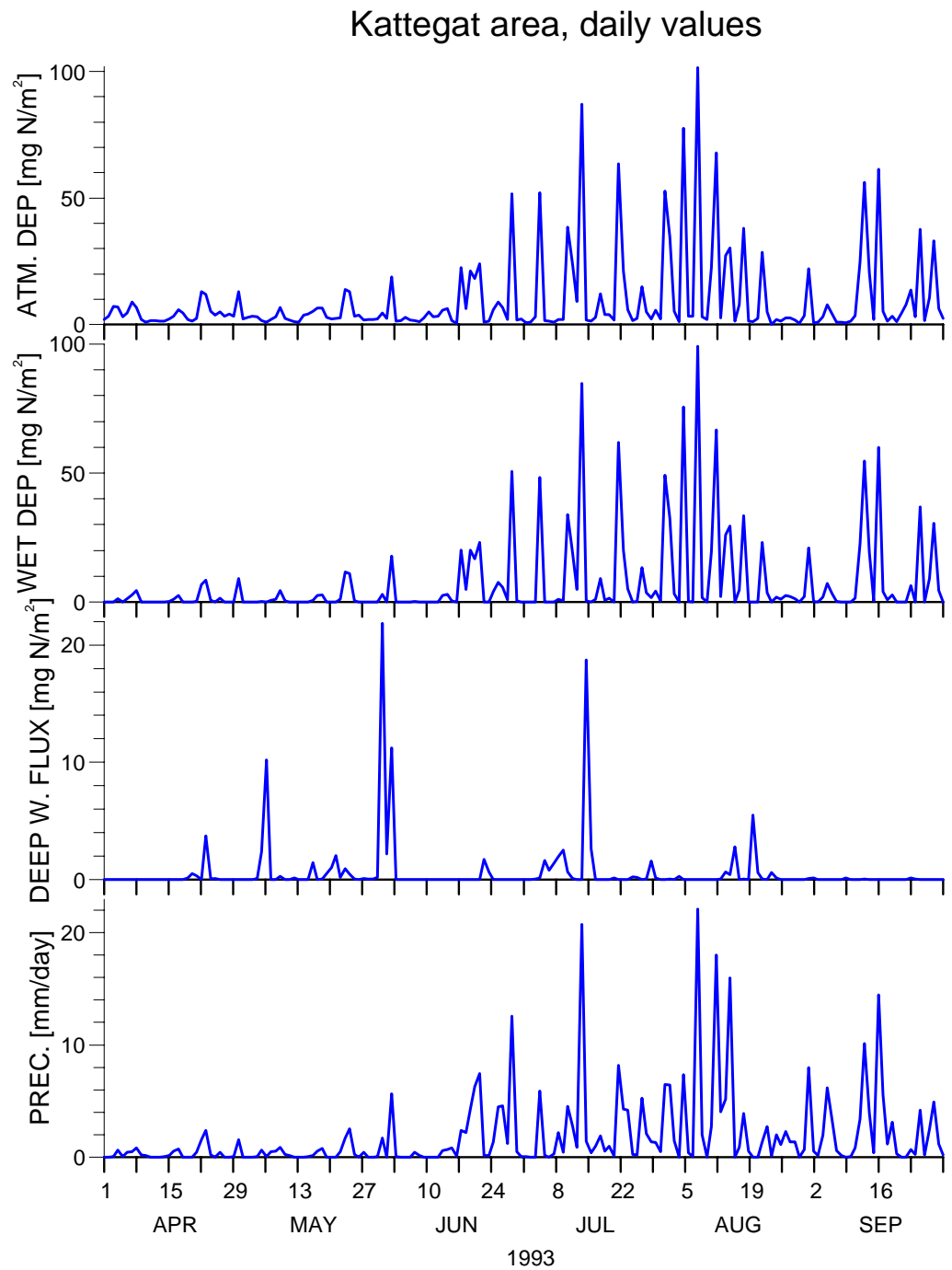
*Figure VI. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1991.*



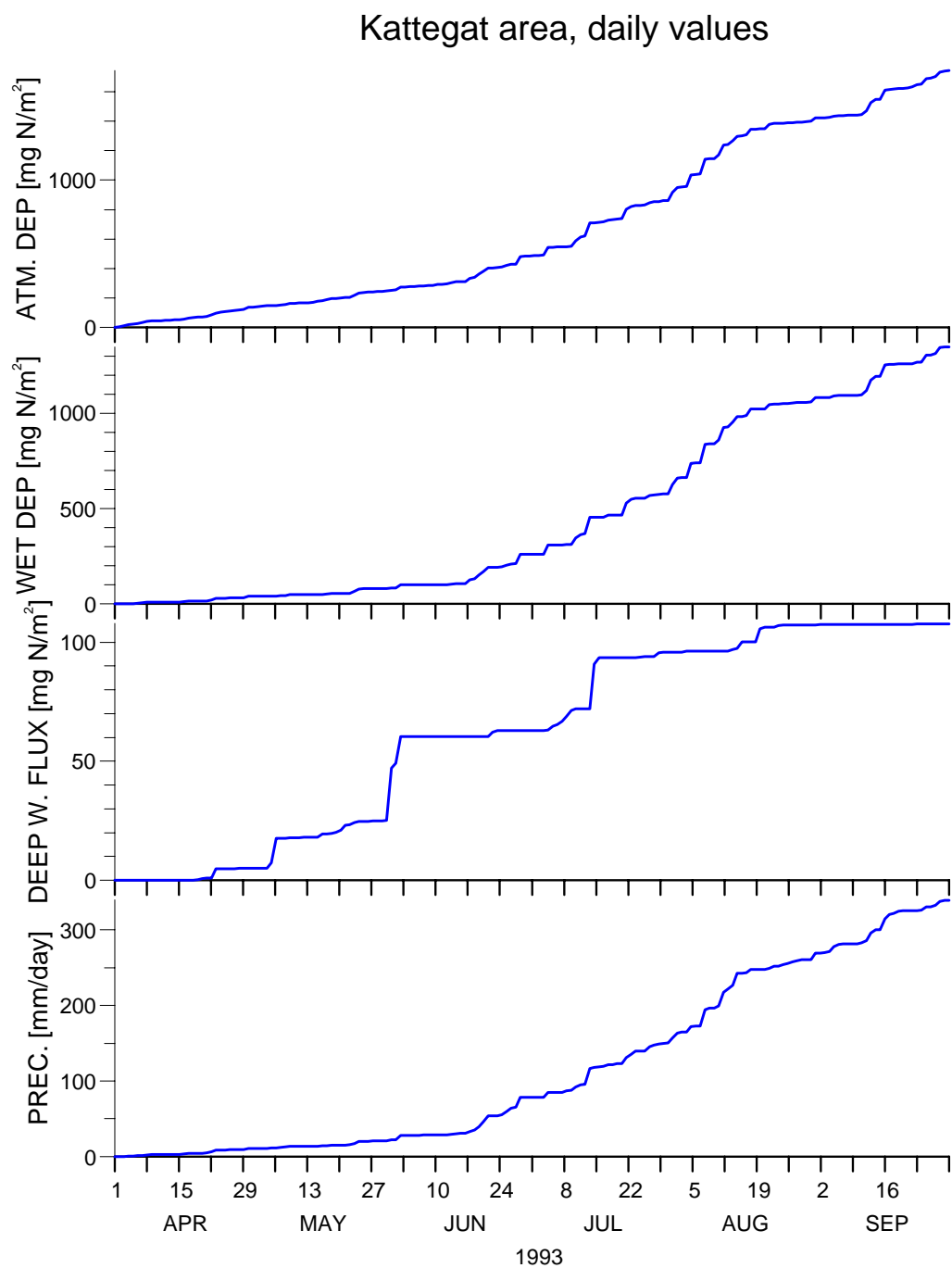
*Figure VII. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1992.*



*Figure VIII. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1992.*

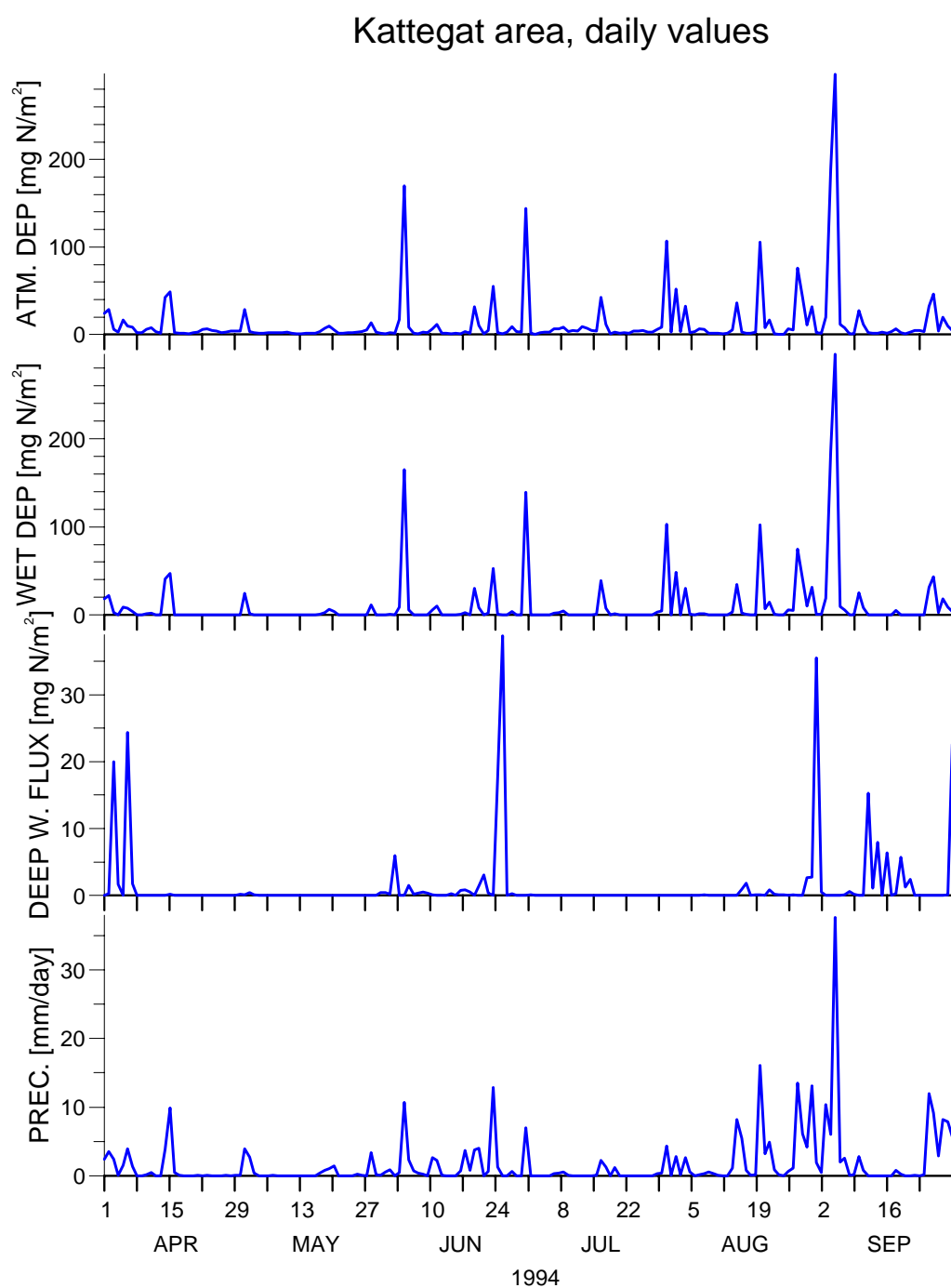


*Figure IX. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1993.*

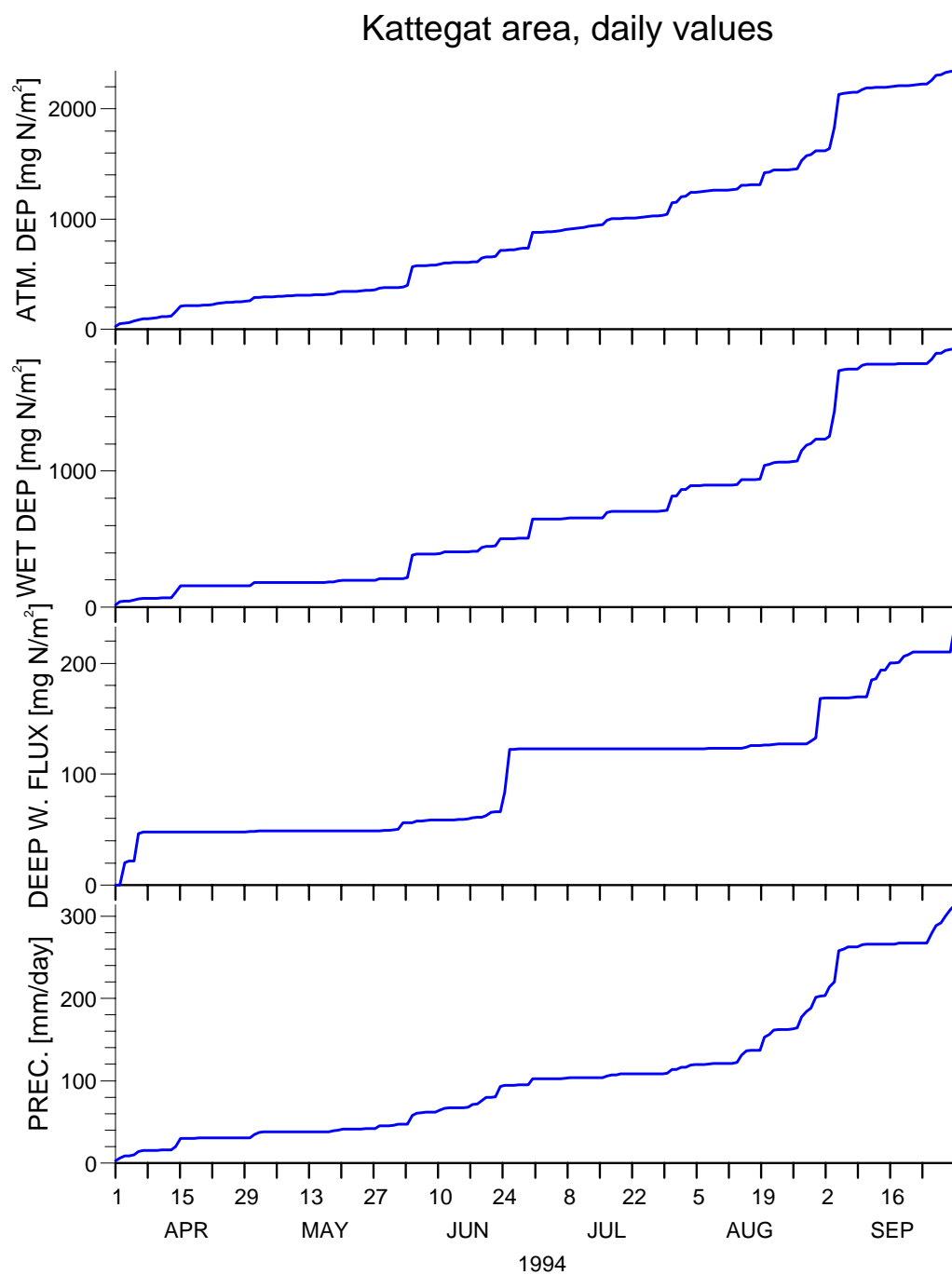


*Figure X. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1993*

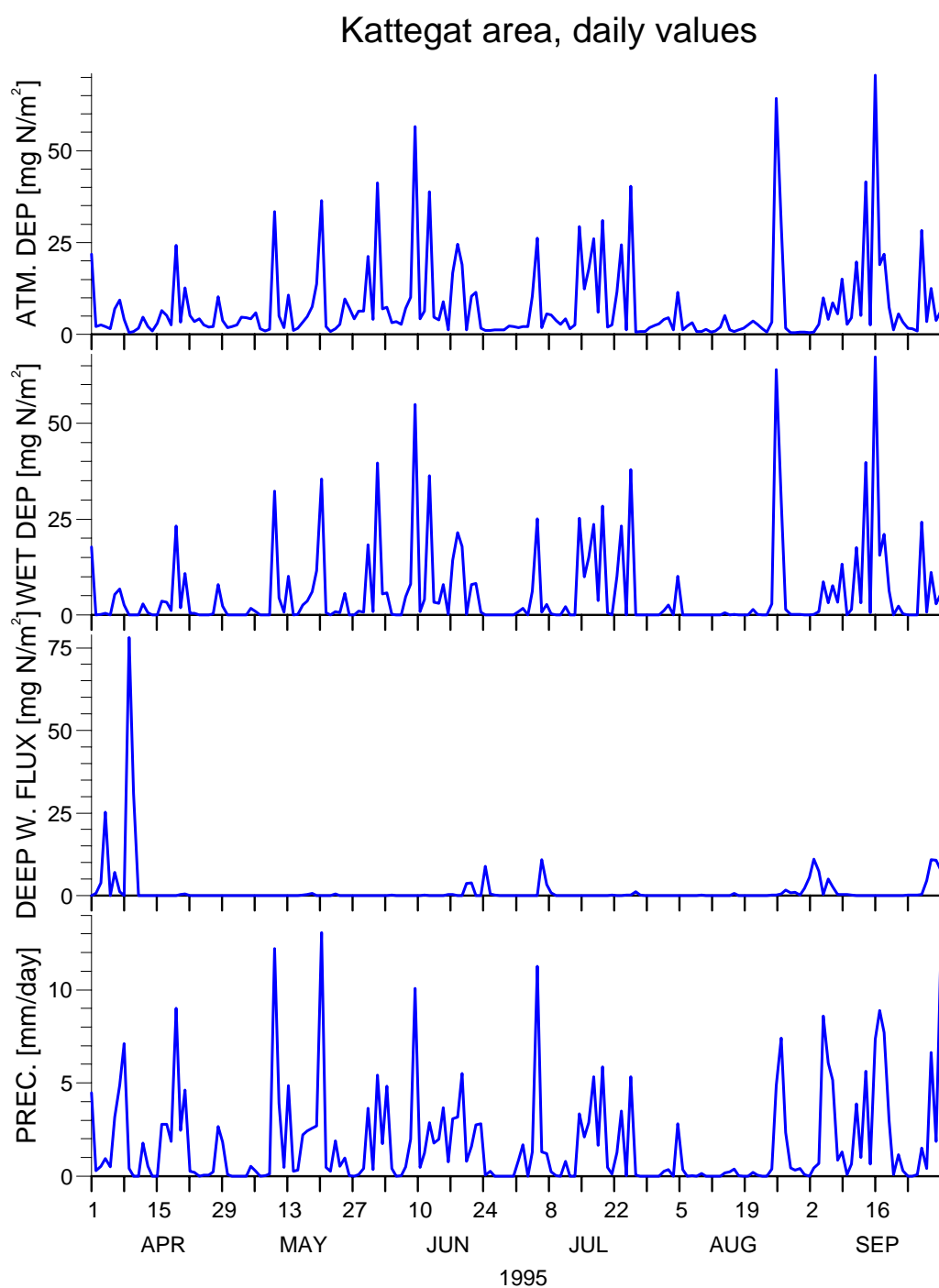




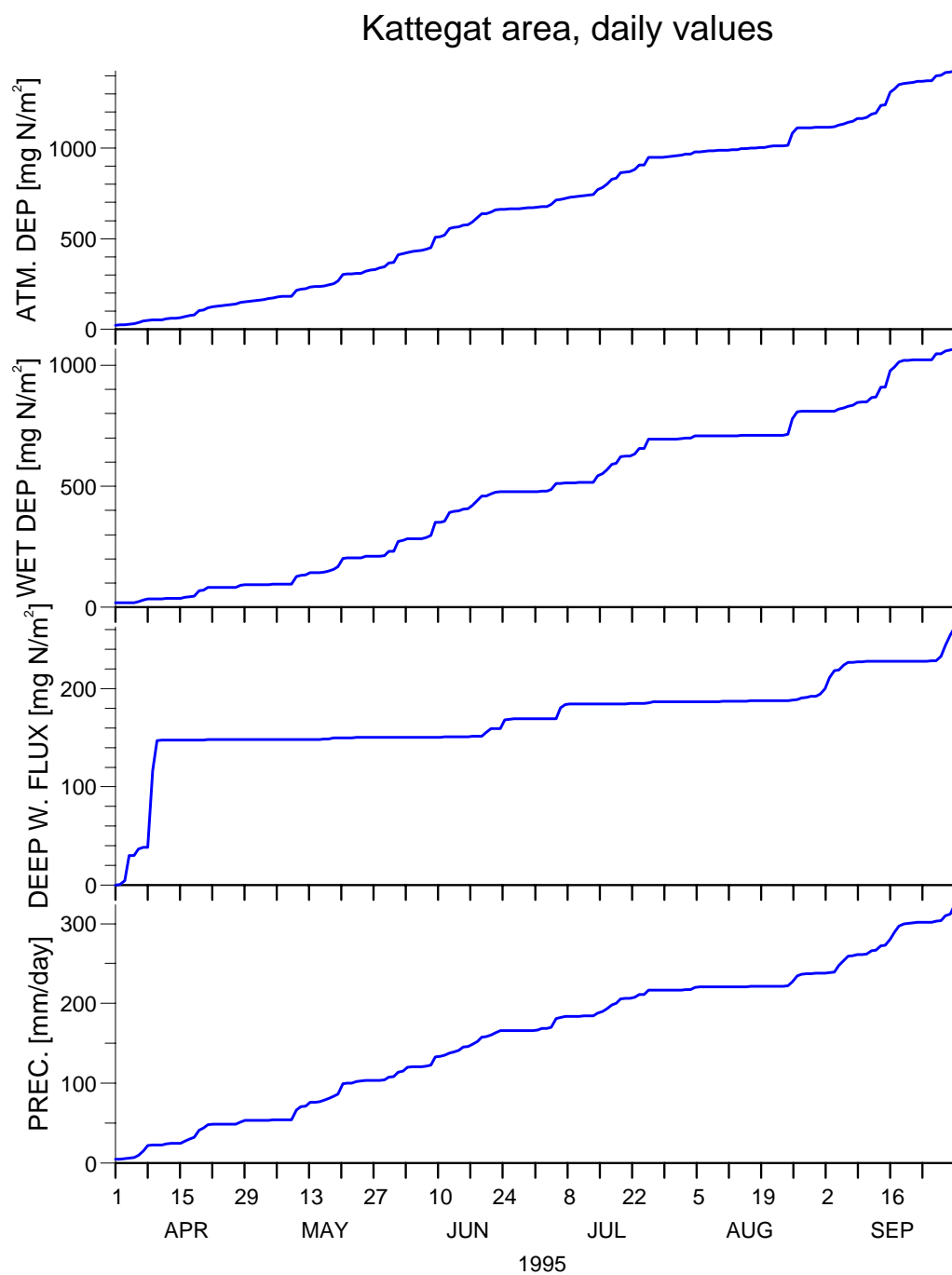
*Figure XI. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1994.*



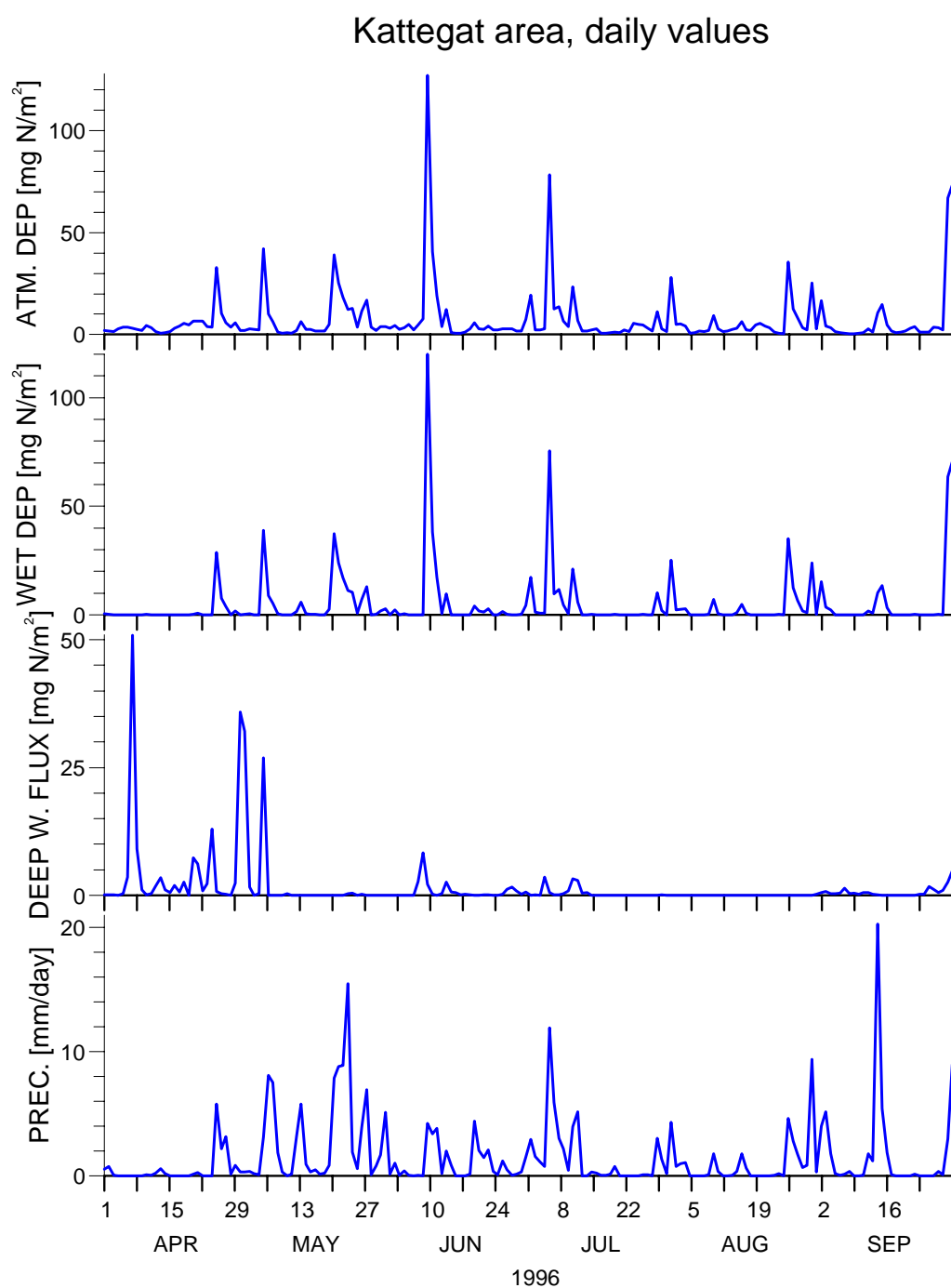
*Figure XII. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1994*



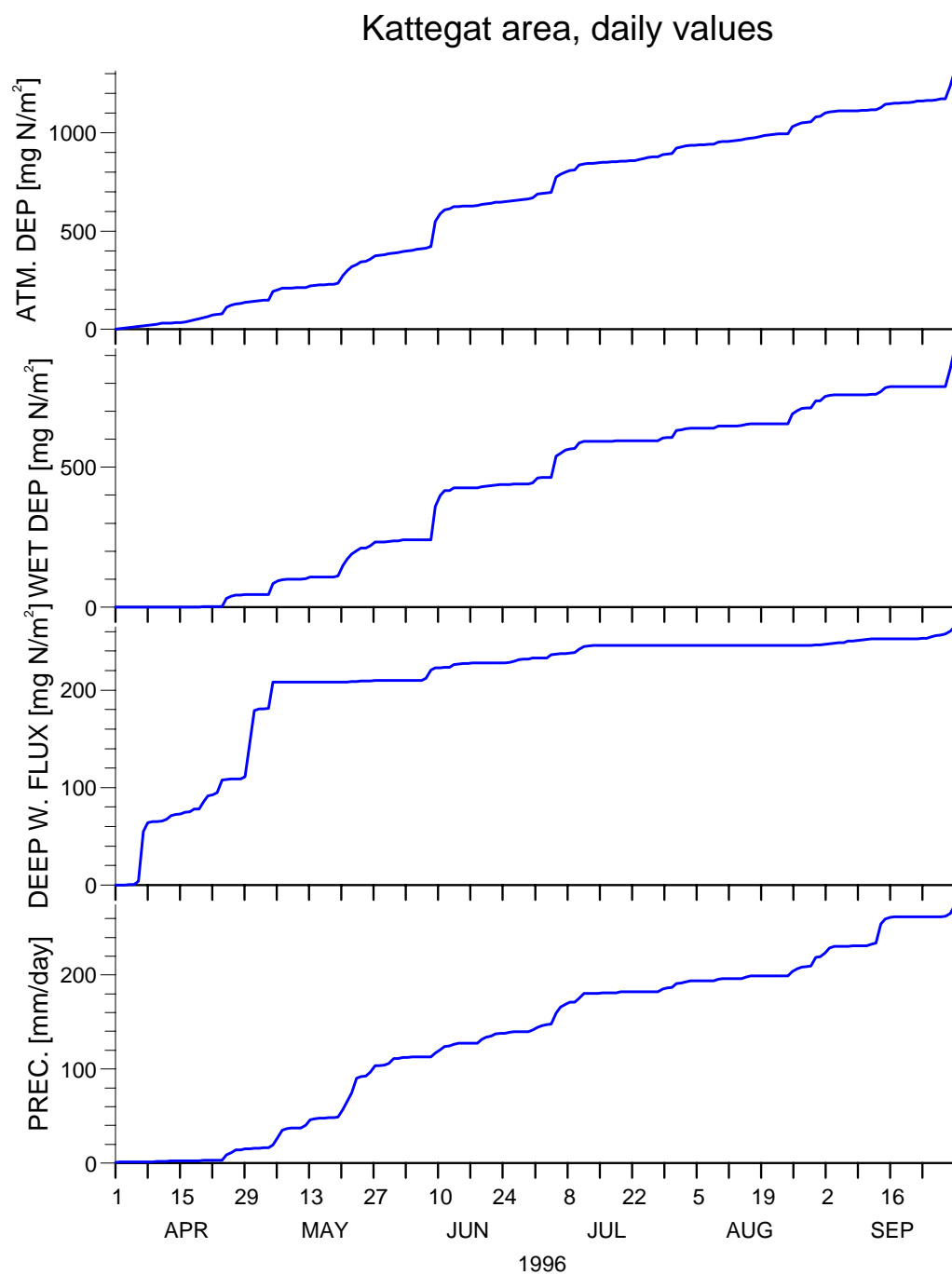
*Figure XIII. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1995.*



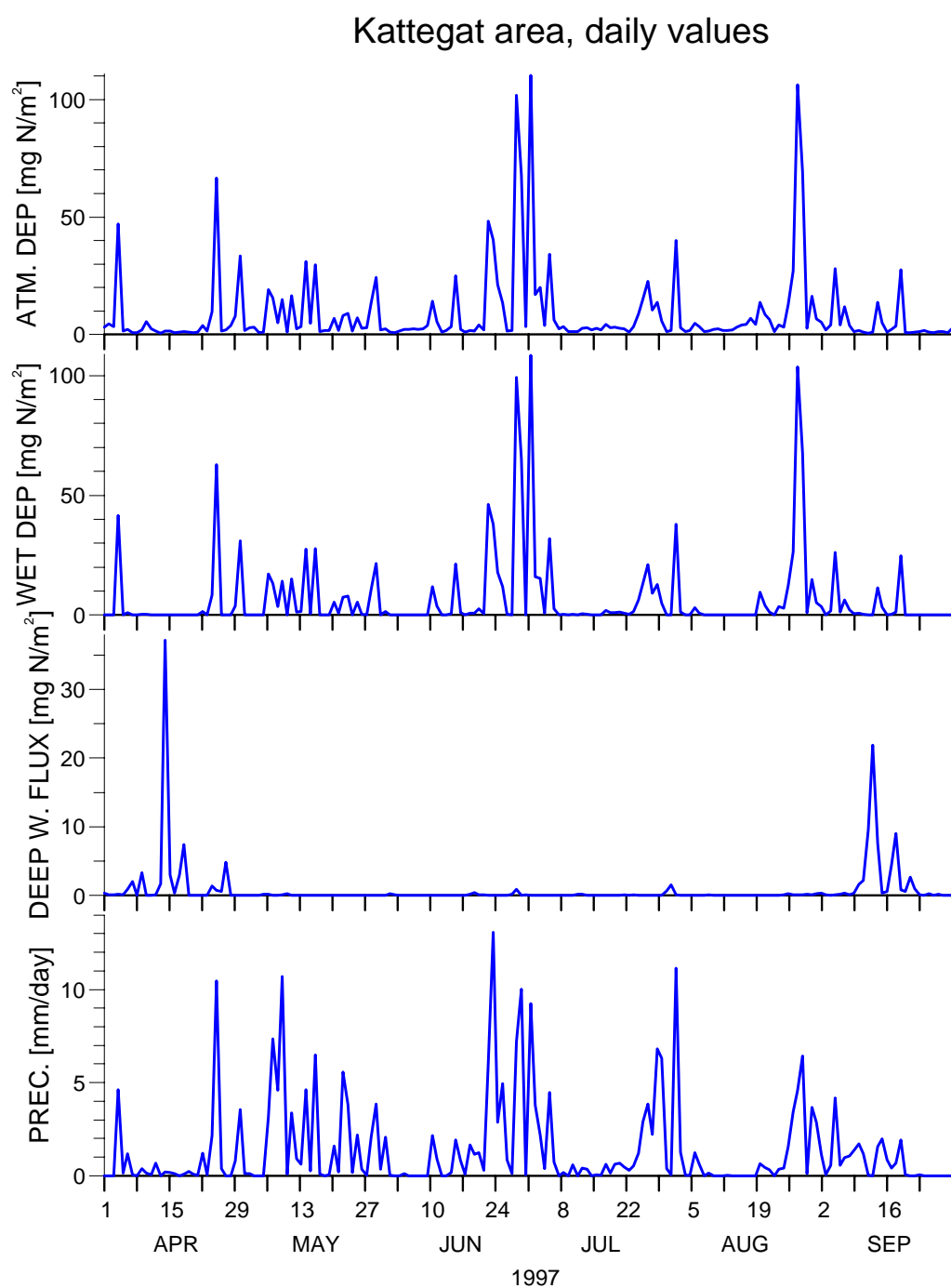
*Figure XIV. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1995*



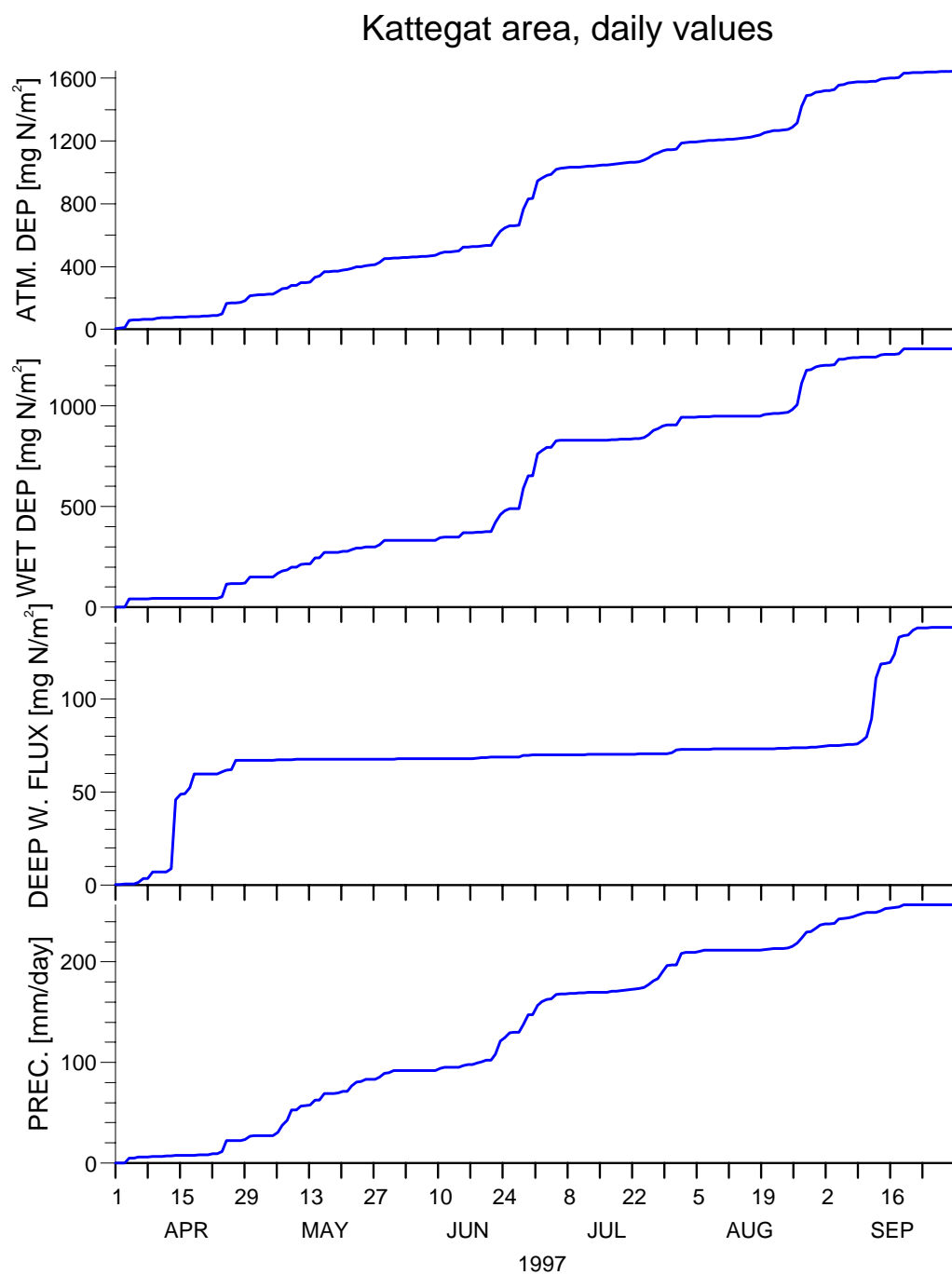
*Figure XV. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1996.*



*Figure XVI. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1996*

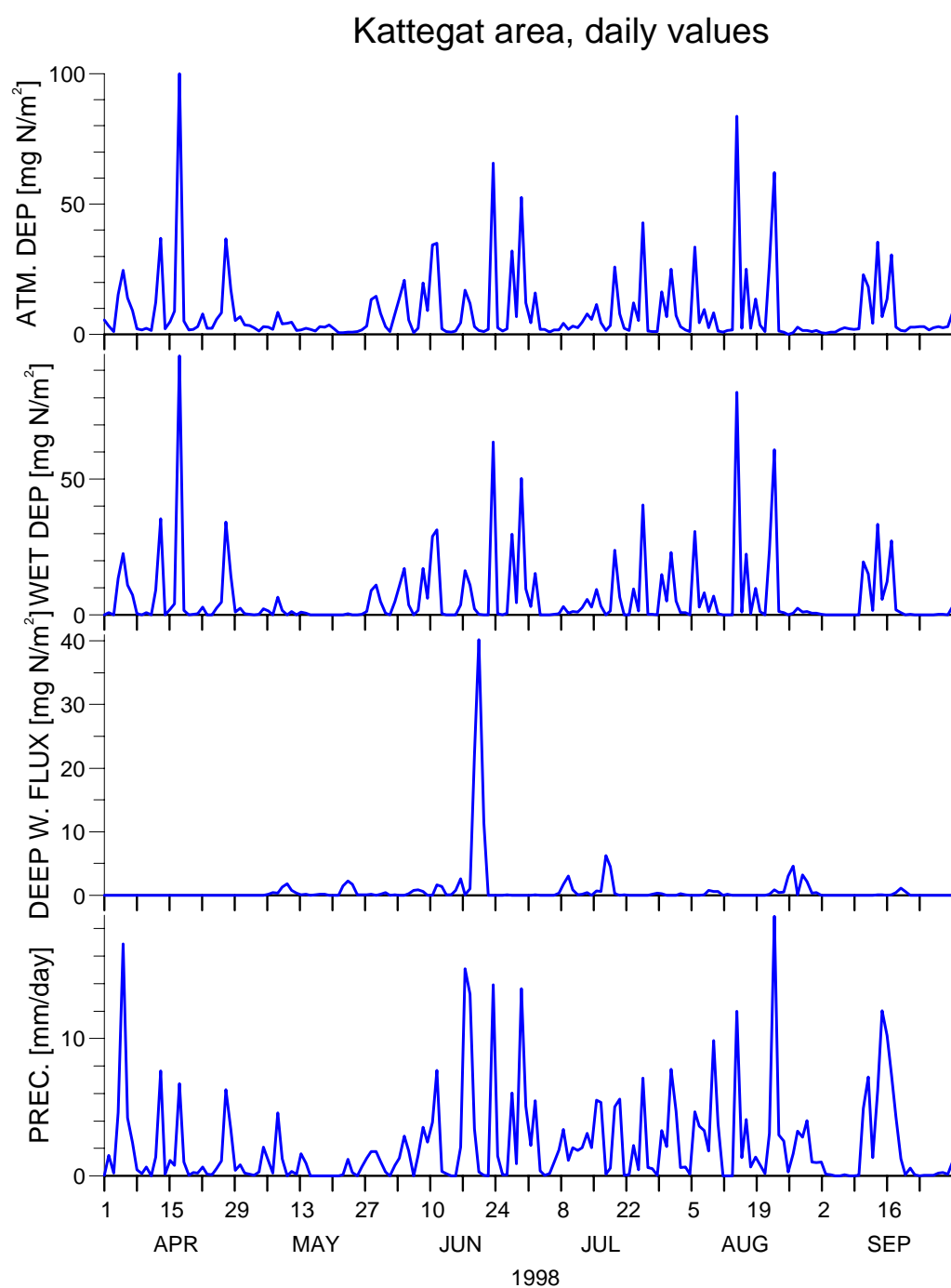


*Figure XVII. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1997.*

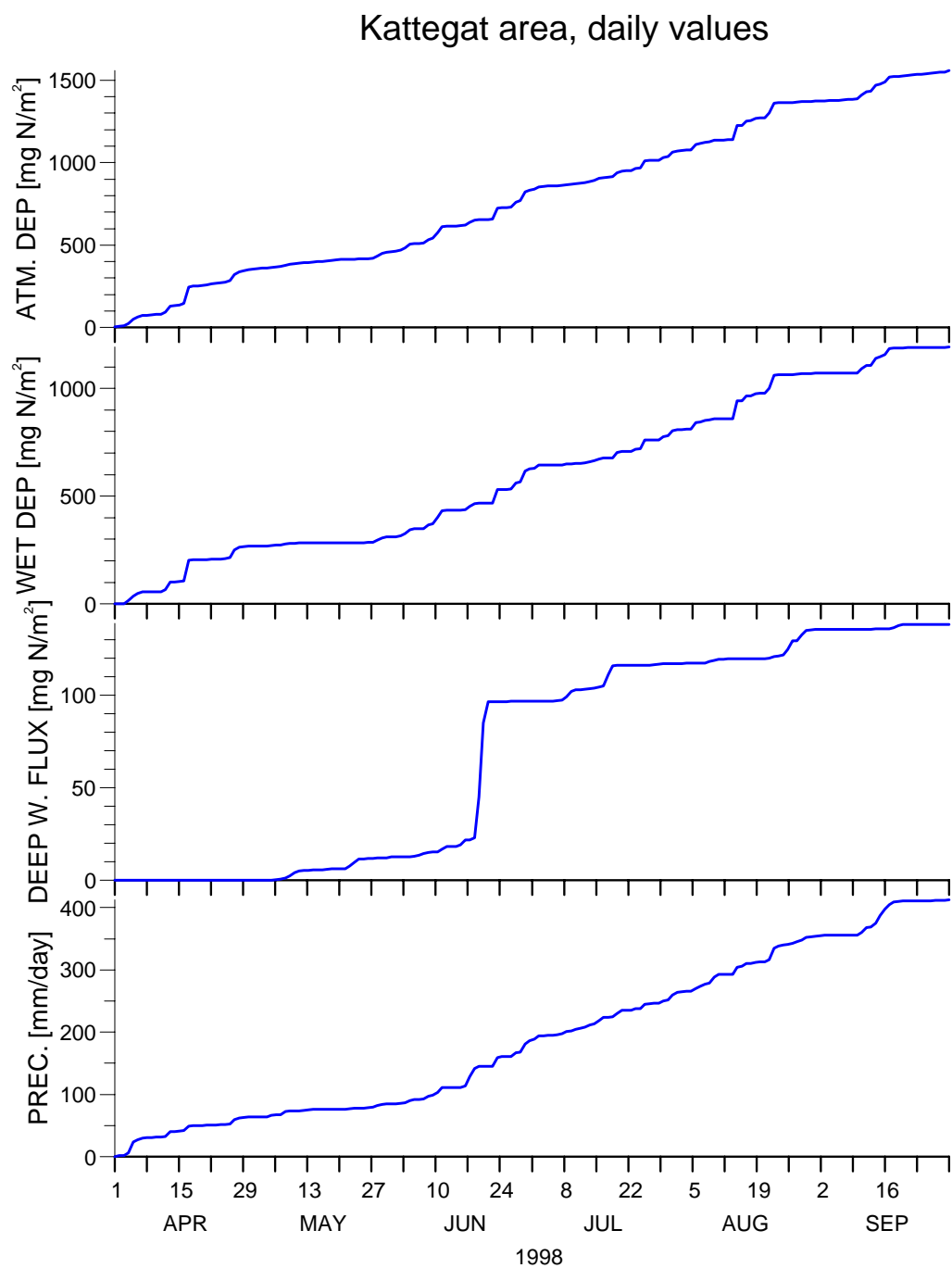


*Figure XVIII. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1997*

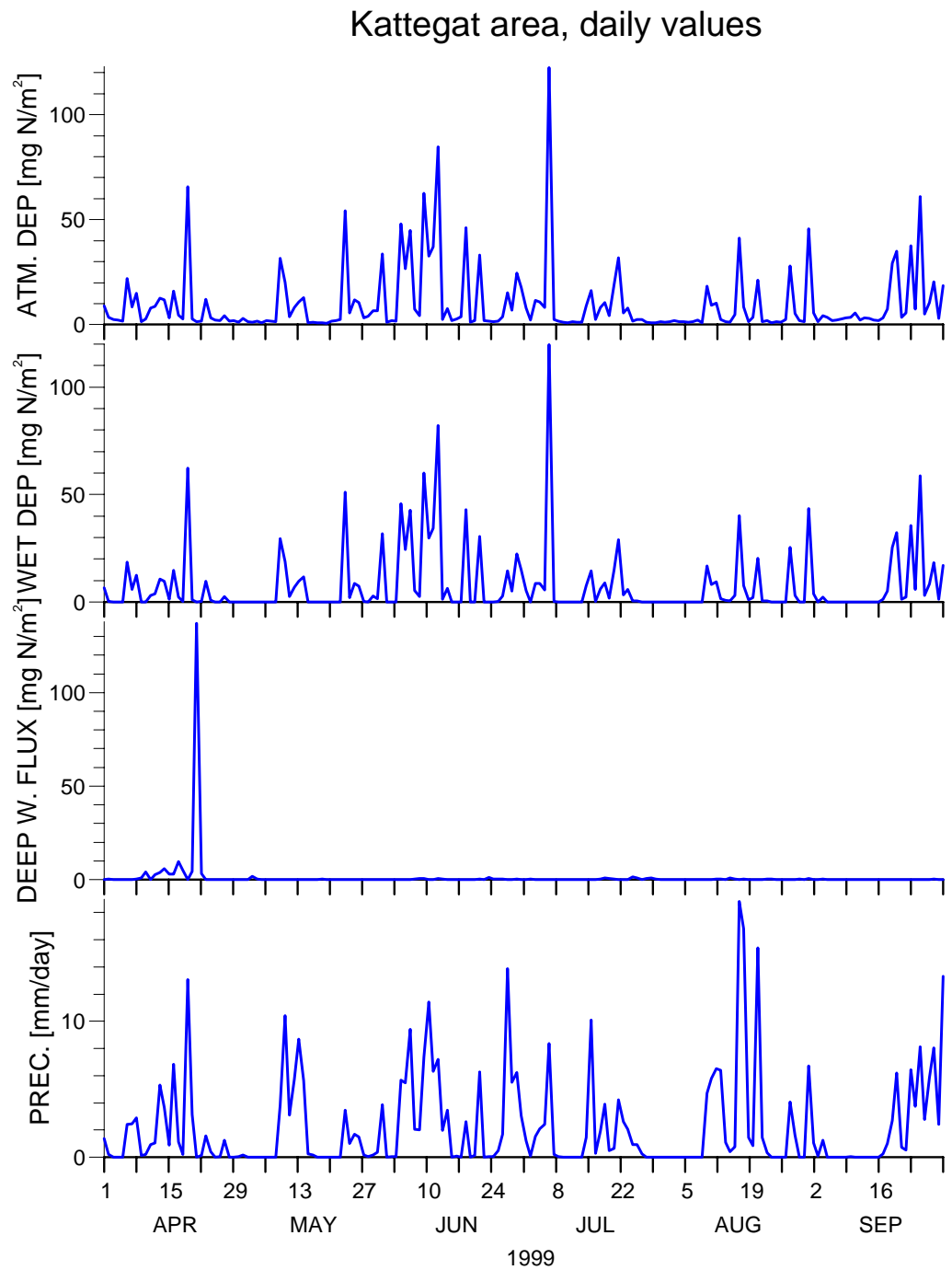




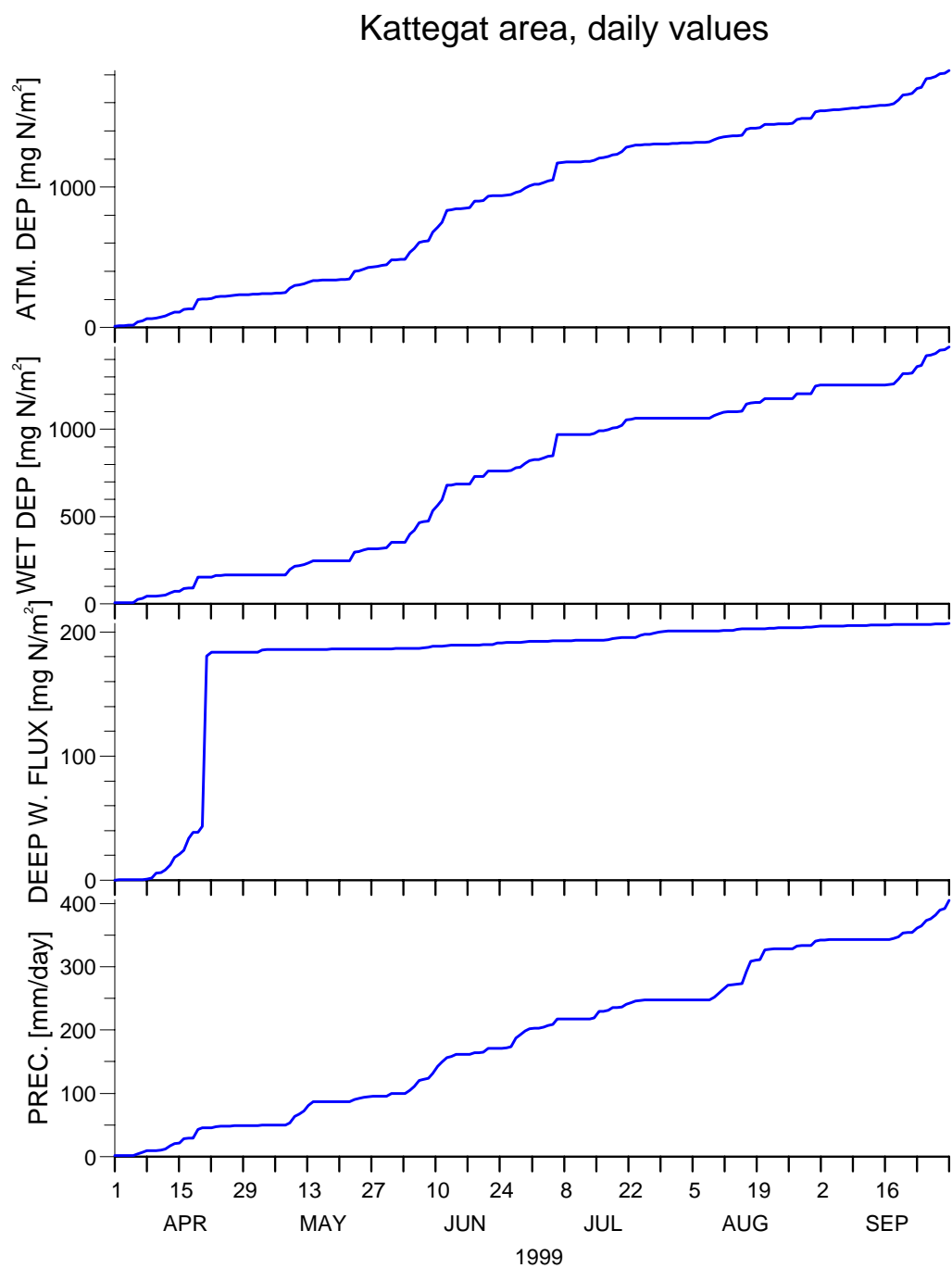
*Figure XIX. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1998.*



*Figure XX. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1998.*



*Figure XXI. Daily values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with daily values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1999.*



*Figure XXII. Accumulated values of atmospheric total deposition and wet deposition of nitrogen as calculated with the ACDEP model together with accumulated values of the flux of nitrogen from the bottom waters to the marine surface layer calculated by a hydrodynamic model and precipitation for April to September 1999.*

## MEAD retrospective analysis report

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G. Geernaert, P. Henriksen, C. Ambelas Skjøth, M. Johnsson.

ISBN	ISSN
87-550-3164-1 (Internet)	0106-2840
Department or group	Date
Wind Energy Department	January 2003
Groups own reg. number(s)	Project/contract No(s)
EU-MEAD-1100-062-1	EVK3-CT-1999-00014

## Sponsorship

European Union, under its Vth Framework Programme

Pages	Tables	Illustrations	References
91	10	51	24

## Abstract (Max. 2000 characters)

The retrospective analysis investigates links between atmospheric nitrogen deposition and algal bloom development in the Kattegat Sea from April to September 1989-1999. The analysis is based on atmospheric deposition model results from the ACDEP model, hydrodynamic deep-water flux results, phytoplankton abundance observations from Danish and Swedish marine monitoring stations and optical satellite data. Approximately 70 % of the atmospheric deposition consists of wet deposition of highly episodic nature. The atmospheric deposition of nitrogen is of the same order of magnitude as the flux from the bottom waters. Yet the cumulative atmospheric deposition is always larger than the marine deep-water flux. The mixing of nutrient-rich water from below the pycnocline into the euphotic zone is also a process of highly episodic character and provides sufficient nitrogen to the euphotic zone to sustain larger algae blooms. The two nitrogen loading processes are correlated – mainly because both are to some extent related to the wind velocity – and the nitrogen input from both processes enables the build-up of algae blooms. Furthermore, the nitrogen supplied on a single day cannot sustain a bloom with an increase above 0.5 µg/l chlorophyll a, but several consecutive days of high nitrogen inputs create the potential for blooms. The physical and chemical conditions before and during a bloom revealed that blooms occurred under higher salinity and wind conditions on 2-6 days prior to the observed bloom. Blooms were dominated by diatoms and dinoflagellates species. Four algal blooms events were identified in the years 1990-1992. Chlorophyll a maps from SeaWiFS satellite are compare well to in-situ observations from the ScanFish mounted at a moving ship.